Modelling the Surface Hydrology of Khet Systems in Nepal during Monsoon Storms

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I hereby declare that the work presented in this thesis is my own and has not been submitted elsewhere for any award

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Abstract

Population pressure and consequent land use change is perceived to be leading to an increase in khet (rice paddy) cultivation in Nepal. Theoretically, in monsoon storms khet systems should provide temporary stores for hillslope runoff, beneficially reducing the quickflow component of rivers and their susceptibility to flooding. This research examines this hypothesis through the development of a computer model to replicate and thus better understand the surface hydrology of khet systems.

The KhetFlow model was conceived in a deterministic manner, based on a continuity equation describing change of water storage in khet terraces. Development of the model is described through the structure advocated by Beven (2012), whereby perceptions are hardened through perceptual and conceptual models to a working procedural model, to be then calibrated and validated.

Perceptions of the controlling processes were gained through general observation, a prototype model, a pilot study and extended fieldwork in Nepal which together with sensitivity analysis indicated that, as would be expected, the system was most responsive to rainfall (and rainfall enhanced irrigation inflow). Also of importance was the interaction between terraces, the division of the hillside into khet subsystems and the interaction between these subsystems. From a modelling point of view the most important control was the need to maintain a water balance throughout the system.

The model was calibrated against field data collected in Nepal and found to be of acceptable accuracy. Using the values derived during calibration, the model was validated against different field data and then deployed in a predictive capacity to examine the hydrological behaviour of khet systems in a variety of plausible situations. These applications suggested that khet systems operate in an efficient manner during storms, even when storm frequencies are high; but have limited capacity to buffer storm water, even when initially dry. However, contrary to the original working hypothesis, very high levels of quickflow generation were predicted, particularly during heavier storms.

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Chapter 1: Introduction and Research Background

1.1 Introduction

The Federal Democratic Republic of Nepal is a sovereign state located in the Himalayan region. The country has been subject to rapid population growth which has placed pressure on the physical environment, especially during the last 60 years or so. The population almost doubled, increasing from 8.4 million to 15.0 million, between 1951 and 1981 (Ives and Messerli, 1989) and has since increased further. The 2001and 2011 censuses recorded a population of 23.5 and 27 million respectively (Population Census, 2001; Central Bureau of Statistics, 2012). The severity of the consequences of this population pressure has been subject to considerable debate. This thesis considers the effect on hillslope hydrology of the increase in khet (rice paddy) cultivation occurring because of the need to intensify agriculture to meet the needs of a growing population.

Nepal is a land-locked country of approximately 147,000 km^2, separating the regional powers of China to the north and India to the south along its 800 km east-west axis. The north-south axis, varying in length between only 90 km and 230 km, experiences the greatest topographic gradient on Earth as it rises from near sea level at the border with the northern Indian plains to the 8,000 m plus peaks of the High Himalaya. The Middle Hills, in which this research was based, range from less than 1,000 m above sea level in The Terai in the south to over 2,000 m above sea level in the north. The Middle Hills occupy approximately 30% of the total land area of Nepal (Carson, 1992), including 51% of the agricultural land, with average holdings of less than 1 ha. Approximately 52% of the population of Nepal live there, most of whom rely on subsistence agriculture (Central Bureau of Statistics, 1996; 1999).

Ives and Messerli (1989) recount that throughout the 1970's and early 1980's it was perceived by many conservationists, scientists and administrators that because of the increase in population the physical environment of Nepal was locked into a series of interlinked downward degradational cycles. Ives and Messerli (1989) refer to this as ‘The Theory of Himalayan Degradation’, an expression that became widely used (see Section 1.2). The theory predicted that ultimately environmental disaster on a scale seen in many countries in sub-Saharan Africa was possible in the Himalayan Region. However, since the mid-1980’s several researchers, particularly Ives and Messerli (1989), have suggested that the hypothesis might be inaccurate and that huge resources could be misdirected trying to resolve a problem not properly understood. They proposed that the ‘Himalayan Degradation’ hypothesis relied too heavily on observation backed by a limited number of short period studies and they and others thought that much of the prevailing research and its conclusions were based on a narrow and possibly flawed data set (Thompson and Warburton, 1985; Gilmour, 1991).

The following review of ‘The Himalayan Dilemma’ (Ives and Messerli, 1989) provides the context in which this thesis should be viewed and is summarised from Gardner et al. (2000), Mawdesley et al. (1998) and Gardner and Mawdesley (1997).

1.2 The Himalayan Dilemma

The physical environment of Nepal is defined by two opposing geomorphological forces, the orogenesis caused by the Indian tectonic plate subducting beneath that of the Central Asian plate and the denudational effect of the monsoon, one of the world’s most powerful weather systems. The conjunction of these two geomorphological agents ensures that this is a physically dynamic and vulnerable environment, subject to tectonic activity and severe erosional forces.

Within this environment, human exploitation of physical resources has been sustainable over thousands of years (as is proved by the continued existence of these resources). However, this exploitation could be jeopardised by (in geomorphological terms) sudden change. One such change, operating on a time scale of tens of years, is a rapid increase in population and the resultant requirement for greater exploitation of resources. Population increases have resulted from the beneficial introduction of medicine and modern health care, including a sustained programme to suppress malaria, which have led to a substantial reduction in mortality, particularly infant mortality, and an increase in life expectancy (Goldstein et al., 1983).

Many researchers reported negative consequences from the resultant population pressure on resources; notably Eckholm (1975, 1976), Sterling (1976) and Myres (1986). Ives and Messerli (1989) labelled the increasing alarmist hypothesis ‘The Theory of Himalayan Degradation’, believing that the “accumulated perspective” was overly pessimistic and seriously distorted. Ives and Messerli (1989) explain that the theory is founded on the concept of a series of interlinked negative feedback loops presumed to be causing severe degradation of the landscape and leading to inevitable environmental disaster. The hypothesis postulates that population expansion has led not only to demand for more agricultural land but related pressure on forest, which has important implications for the Nepali subsistence farming system. Sustainable forest is vital, partly for fuelwood and construction timber, but most importantly for cattle fodder. Cattle manure can also be used to sustain the fertility of the soil but failure to apply it leads to dramatic falls in crop yield and, as has happened in other parts of the region, ultimate abandonment of previously productive land when it becomes infertile (Ramakrishnan, 1992). Increased demand for forest land for cultivation and increased demand on the reducing forest area for its products has ostensibly led to massive deforestation, to the extent that in 1979 the World Bank predicted that there would be no accessible forest cover remaining in Nepal by the year 2000 (World Bank, 1979).

It was also hypothesised that disturbance of previously forested or grassed land had other implications, particularly a purported disastrous increase in soil erosion (Eckholm 1975, 1976; Myres 1986). The steady erosion of soil is inevitable in the region with not only the greatest relative relief on earth but 2,000 to 10,000 mm of rain per annum, mostly concentrated into the months from April to September. Until rapid population growth started in the Middle Hills it can be assumed that soil erosion and land exploitation were in equilibrium, soil being replenished at a rate keeping pace with erosion and human exploitation (again, as is shown by its continued existence). A major component of the Himalayan Degradation Theory is the suggestion that population pressure and land use change alters this equilibrium and creates pressure to bring more marginal and less fertile land on steeper slopes higher in the catchment into production by converting it into bench terraces (bariland). Soil erosion thus increases, as does the incidence of highly damaging landslides (Eckholm, 1976).

As runoff is considered to be much higher from bariland than forested areas (Gardner and Jenkins, 1995) this is thought to give further impetus to erosion. Increased runoff will also lead to a greater quickflow component of catchment response, resulting in increased monsoonal flooding, river diversions and higher suspended loads accelerating siltation of reservoirs and shortening the useful operating life of hydroelectric and irrigation schemes. Conversely, because of lower infiltration, base flow in the dry season will be lower and cause the consequent drying up of springs and wells and a reduction of water in irrigation systems, reducing crop productivity at that time.

Trans-border consequences have also been suggested as sediment would be carried downstream, potentially damaging hydro-related projects in India and Bangladesh (Eckholm, 1976). Suspended loads would drop when energy is lost as the rivers cross the North Indian plains, widening watercourses and intensifying flooding in both India and Bangladesh. It is hypothesised that such increased flooding is responsible for the destruction of rich lowland farmland by deposits of river gravel and sand on previously fertile ground. This led to the charge that a few million subsistence farmers in the hills of Nepal were endangering the environment of hundreds of millions, equally dependent on subsistence agriculture, in the lowlands (World Resources Institute, 1985).

The general scenario was that at many points in this complex environment thresholds had been crossed and mutually supporting systems had been weakened to the extent that the ‘Himalayan Degradation Theory’ represented a downward environmental spiral from which it would be impossible to break out. Ives and Messerli (1989) summarise the perceived net results of the various destabilising processes as absolute deforestation of the Middle Hills, lower crop productivity, a greater proportion of the subsistence farming population with inadequate nutrient intake and progressive mountain desertification. Added to this must be political repercussions if the consequences of mismanagement of the environment in Nepal are negative social and economic implications for India and Bangladesh.

However, from the mid-1980’s several researchers began to state shortcomings in the theory as rigorous field data started to become available with which to test the various hypotheses. Ives and Messerli (1989) suggested that much of the substance of the expounded theories had been based on extrapolation of limited research and data and Thompson and Warburton (1985) state that the data that do exist are often contradictory and fraught with uncertainty. Gardner and Jenkins (1995) cite the Mohonk Conference (1987) as the turning point towards recognition that a more scientific evaluation of environmental process and human interaction was required.

One of the first indications that the situation had been viewed in an oversimplified manner came from extensive analysis of aerial photography of the rates of deforestation (Land Resource Mapping Project, 1986) which showed that within the Middle Hills zone between 1964 and 1979 forest cover actually *increased* by 1.8%. This finding was consistent with research by Mahat et al. (1986) which suggested that deforestation had been a gradual process over several hundred years and culminated in relatively high levels of conversion to cultivated land in the 1940s and 1950s during a period of political uncertainty and when deforestation was promoted by tax concessions, and not in the more recent period of population increase.

1.3 Further Research in Nepal

Whilst issues of deforestation and land degradation have clearly been oversimplified there can be no doubt that land use change was and is causing some problems. Examples of soil erosion, landslides and exploitation of the forest can be readily seen when travelling in The Middle Hills. The need for research over longer time periods to determine the scale of the problem and for more rigorous data on which to base hypotheses and management strategies became accepted. To start to fulfil this need the Royal Geographical Society/Institute of Hydrology/HM Government of Nepal project 'Water, Erosion and Land Management' (1991-4), in the Likhu Khola Valley in the Middle Hills (RGS/IH/HMGN Project), was conceived and undertaken. This Department for International Development funded project was multi-disciplinary and operated on the catchment scale over a three-year period. The basis of the project was an integrated analysis of the hydrological, geomorphological, sedimentalogical, biological and agricultural systems operating in selected river basins. Its purpose was to understand the primary processes relevant to the theory of degradation in the Himalayan region and the study on which this thesis is based originated as part of this wider research project.

At the conclusion of the RGS/IH/HMGN project in the Likhu Khola, Gardner and Jenkins (1995) proposed that land degradation was, in general, not a major problem in Nepal. Similarly, Gardner and Gerard (1995) found that the effect of landsliding, though sometimes visually dramatic, was much less than might be suggested as most landslides were small terrace slumps and, even in the case of larger land movements, much soil was re-incorporated into the hillside system by the farmer only a few metres down the slope. However, the RGS/IH/HMGN research obtained only limited erosion data from bariland and the data were not of sufficient scope to fully resolve concerns raised by previous researchers of excessive erosion from such systems; outward-sloping, rain-fed terrace systems, usually higher in the catchment and usually planted with wheat and mustard in winter and maize in summer. In further research in Western Nepal, Gardner et al. (2000) conducted additional field trials and confirmed the findings of relatively low levels of soil loss from bariland.

This study demonstrated that although soil loss considerably higher than the tolerance threshold was possible under certain conditions, widespread new conservation measures were not needed. Aggravated soil erosion could always be explained by a specific cause, such as high water run-on or localised management practices, leading them to conclude that the approach required to address the problem of excess surface soil erosion should be that of risk awareness of the particular conditions at the local scale and the management of those conditions. Acharya et al. (2007) concurred, in particular demonstrating the benefits of diverting surface run-on away from the bari terraces. Acharya et al. (2008) also demonstrated the benefits of controlled interventions such as strip cropping and mulch addition in the Palpa district of Nepal where, for cultural reasons, bari terraces are characterised by large fields with slope angles of 20 to 35 degrees, contrasting to the smaller, flat, moderately-sloped terraces of most Middle Hill areas.

1.4 Khetland Issues

Three main types of agricultural land are present in Nepal; grassland for grazing cattle and goats, bariland and khetland; and it has been previously noted that forested areas also have an agricultural function in the provision of animal fodder. Bariland consists of outward sloping, rainfed, drained bench terraces. Khetland, the focus of this PhD, refers to any irrigated, flat terrace system constructed with a lip to facilitate ponding and cultivation of rice. Figures 2.2, 2.3, 2.4 and 2.5 show typical khet configurations and Section 2.5 describes the composition of khetland in more detail.

The issues on khetland are of a different nature from other land uses. The Likhu Khola valley, the location of the RGS/IH/HMGN project, includes each representative land use system and is illustrative of the makeup of a typical Middle Hills catchment. Gardner and Jenkins (1995) explain that the natural cover of the Middle Hills is forest, sub-tropical and tropical hardwoods on the lower slopes and mixed broadleaved forests at higher altitude. However, population pressure and particularly the proximity to the Kathmandu market has brought extensive land use change and introduced intense management regimes, including annual triple cropping in some areas. Growth in regional population and a greater requirement for food has led to clearance of the original forest to provide cultivated land. If conditions allow, farmers prefer to farm khet as the yield, in terms of food or cash, is approximately five times greater than that from bari (Gardner and Jenkins, 1995). Soil erosion from khet is negligible as this system of agriculture acts as a buffer to soil loss. Soil is trapped as suspended sediment entering the system settles in the ponded water of the khet and is also inhibited from further transportation by the terrace bund (lip) (Gardner and Jenkins, 1995).

However khetland, whether converted from forest, grassland or existing agricultural systems, fundamentally alters the surface hydrology of the hillslope. This, in turn, has implications for the response of rivers and streams in the catchment to monsoon storms and ultimately for the little understood trans-border links with the lowland plains of India and Bangladesh. If khetland restricts quickflow to the catchment waterways it would be expected that the propensity for flooding would be reduced. Also, in ponded conditions infiltration would be expected to increase, leading to higher base flow and increased irrigation water availability in the dry season, improving the productivity of crops during months when water is scarce.

1.5 Overall Research Aim

The purpose of this research was to provide greater understanding of khetland surface hydrology. Gardner and Jenkins (1995) state in the RGS/IH/HMGN project report that “The routing of water through the canal system and the khetland, will introduce a substantial delay into the natural hydrological system in areas where the proportion of khetland is high. This will lower the potentially high peak discharges during heavy storm events”. This provided the working hypothesis at the start of this research; that khet systems, acting as a buffer for soil transportation, would also act as a buffer to hillslope runoff. The premise being that ponding in khet on the hillslopes would act as a temporary store of water, attenuating the flow of runoff during monsoon storms. If this were true then this would be a beneficial result of land use change, slowing the response of rivers in the catchment to monsoon storms.

But other relevant questions can also be asked as hydrological response to storms may not be consistent for several reasons: the antecedent hydrological state of the terraces may cause runoff variation; as might the size and frequency of rain storms and the structure and connectivity of terrace systems; it may be possible to alter the physical configuration of terraces to mitigate excess runoff. It is also possible that in certain circumstances, perhaps during frequent and /or heavy storms when terraces were near capacity, the need to directly drain excess water from terraces to avoid overflow and system breakdown would mean that runoff from khetland was higher than from other land uses and quickened catchment response. The aim of this research is thus also to develop a means to better understand the surface hydrology of khet systems.

As is explained in detail in Chapters 2 and 3, the change in storage of a single terrace is quantified relatively easily at a scale appropriate to this research. Transfer rates between terraces are also readily quantifiable and initial and boundary conditions are less problematic than is often the case in hydrological research, again at an appropriate scale. Because of this structured design of both individual terraces and terrace systems and the opportunity to collect empirical data for testing purposes it was decided that the aims of this research would be best achieved by the development of a computer model.

The overall aim of this research was therefore to develop and deploy a computer model to provide greater understanding of the surface hydrological response of khet terrace systems to monsoon storms at the hillslope scale. This was achieved through understanding the surface hydrology of rice terraces, by field measurements and model experimentation, at the lesser scale of individual terraces and small khet systems. This provided the knowledge and data to allow the model to be used for speculation regarding larger khet systems and the hillslope scale.

Additionally, as it is difficult, time consuming and expensive to gather empirical field data in the Himalayan region and it will be easier to undertake similar research in this remote area if an accurate model can be developed to replicate physical processes, an important consideration in the development of the model was the ability to be able to reliably replicate processes from as few variables as possible, ideally from those that are relatively easily measured in the field.

Within the overall aim the specific objectives of the research were:

1. To conceive, develop and test a computer model to replicate, through the use of mathematical algorithms, the flow of water through khet terrace systems.

2. To undertake extensive field studies on khet systems in The Middle Hills of Nepal during monsoon storms to gather data on surface hydrological processes with which to calibrate and validate the model.

3. From these field data and the modelling of khet systems, to ascertain the dominant variables and processes controlling the surface hydrology of khet terraces.

4. To determine the volume and timing of water held in temporary storage in khet terraces and understand the mechanism by which it is released to the main river system, using the field data and the model developed.

5. To explain how the results provided by the model can be utilised and the method adapted to better understand the surface hydrology of khet systems to allow predictions of khet system response to storms at the hillslope scale.

1.6 Thesis Structure

This study commenced before the concept of model development defined in Beven (2012) was originally published in 2001 but the process described therein reflects the experience of this research and provides the structure of the modelling process here reported. Five stages of model development are defined:

1. The Perceptual Model
2. The Conceptual Model
3. The Procedural Model
4. Model Calibration
5. Model Validation

Chapter 2 describes in detail the development of the model through the perceptual, conceptual and procedural stages, where first the dominant processes are identified (perceptual stage), then represented by mathematical equations (conceptual stage) prior to the development of a functional computer simulation (procedural stage).

However, as the study progressed it became evident that the hillside context also had to be properly understood, particularly that the distribution of khet terraces on the hillside and the interaction between the terraces was important to the understanding of the hydrological behaviour of khet systems. This is introduced in Chapter 2 before an explanation of the hillside environment is expanded in Chapter 3, which also provides the context of a literature review and justifies the use of the KhetFlow model for this study . Chapter 4 describes field methods and explains how model predictions were compared to field data.

Chapter 5 examines the sensitivity of terraces and inter-terrace links to changes in the constituent parameters before Chapters 6 and 7 complete the structured approach described in Beven (2012) with Model Calibration and Validation, respectively.

Finally, Chapter 8 concludes the research by undertaking investigative modelling of several environmental scenarios to better understand khet hydrological response. The model is deployed to predict terrace reaction to storms of different magnitude; to predict the breakdown point of terrace systems and the buffering of this by antecedent conditions; and to estimate the amount of water added to the main catchment river if water is diverted to prevent breakdown of the terrace system.

Chapter 2 – Model Description

2.1 A Template for Model Development

This section explains the model in the context of the stages of development outlined by Beven (2012):

1. The Perceptual Model
2. The Conceptual Model
3. The Procedural Model
4. Model Calibration
5. Model Validation

This framework echoes the development of the KhetFlow model, which is designed to simulate the flows and storage of water through flooded terraced hillslopes. This chapter describes the first three stages in model construction; (i) identification of the dominant processes to be incorporated (the perceptual model); (ii) the development of appropriate mathematical representations of these processes (the conceptual model); and (iii) the translation of the mathematical model into a functional computer simulation tool (the procedural model).

Beven (2012) refers to perceptual modelling as a process that “borders on the intangible”, involving the identification and development ideas and preconceptions that describe the functioning of the target system. It can be considered an “intellectual baseline” for the research to follow. Beven (2012) sees the perceptual model as a vital step often not documented by researchers, and suggests that it is probable that each researcher, biased by their own their scientific and cultural heritage and their own individual experience, will formulate a different (perhaps wildly different) model at this stage.

In this research the perceptual model was formulated from a combination of:

- Knowledge accumulated through fieldwork undertaken for the RGS/IH/HMGN project
- Literature from other research in the Middle Hills
- Experimentation with a prototype model
- A pilot study in the Likhu Khola watershed
- Further, extended fieldwork in the Likhu Khola watershed

The Conceptual Model involves the abstraction of the processes identified in the perceptual model into mathematical structures and formulations that facilitate quantitative explanation and prediction. In this research, the conceptual model takes the form of a series of surface and soil water stores linked by transfers. The surface store is the core of the model developed and is described in detail in Section 2.4 below, together with a detailed explanation of transfers in (rainfall, irrigation, inflow from above and return flow) and out (evapotranspiration, seepage and outflow) of this store. The soil water store is recognised but in this study transfers are only included at the scale appropriate to the research question being answered.

The Procedural Model is the translation of the conceptual model into computer code, enabling rapid and repeatable realization of quantitative simulations. The mathematical construction of the model and the manner in which data are manipulated by the model are described in detail in Section 2.6. This is placed in the context of the limitations of modelling, when the current governing paradigms of hydrological modelling are considered as part of the literature review in Section 3.6.

An important consideration when developing the model was that it was essential to replicate the distribution of khet terraces on the hillside and the interaction between them. The chosen model design is appropriate for the highly organised structure of khet terraces systems, which is explained in the sections following. A more complete description of the environmental context and justification of the modelling approach taken are provided in Chapter 3.

The stages of calibration and validation are, in effect, those of testing the accuracy of the model. Calibration provides an initial test against fieldwork and the adjustment of estimated parameters to decide which values afford greatest accuracy. Validation, interpreted in this most simple form, then provides an independent test of the calibrated model against additional field data not used during the calibration stage, to assess the robustness of model accuracy in different situations. These phases of model development are outlined in Chapters 6 and 7 respectively.

2.2 Perceptual Model: Khet Terrace Processes

Khet terrace systems on hillsides are complex. They may comprise of only a few terraces but often are formed by hundreds of interlinked units (illustrated in Figures 3.1 to 3.4). Each terrace receives input from one or more terraces higher on the hillside (or the irrigation system) and discharges into one or more terraces below (or the irrigation system). Reaction of the system to water input is complicated by inputs in any one terrace inducing a response that cascades down the hillside as changes in storage and discharge are reflected in increased or decreased output from each terrace and thus as a change in input of the terrace(s) into which it discharges. This is consequently reflected in, and reinforces, change in storage and discharge from the lower terraces and produces a cumulative effect that propagates downwards through the system.

There are numerous possible routes for water flow and multiple possible temporary storage points. Inputs from rainfall may also be variable, as may be inputs from irrigation systems higher on the hillslope (represented by irrigation inflow), which can change quickly in response to rainfall. Prevailing rates of evapotranspiration, seepage and return flow (which may be related to seepage or be from higher on the hillside) also affect terrace response, as will terrace architecture and conditions such as crop stage and obstructions within drainage channels and from clods of soil on the terrace floor that might restrict flow.

The hydrological functioning of khet terraces is also influenced by the flow and storage of water beneath the surface. Within individual terraces this interacts with the surface hydrology through seepage and return flow (from the terrace above and to the terrace below), particularly under ponded conditions. The subsurface store also receives seepage input from higher in the hillslope and loses water to deeper seepage that will not return to the terrace immediately below; and there is also the possibility for flow in and out laterally. During dry periods if the terrace surface store has emptied the subsurface store will also lose water directly to evaporation and, even when ponded, will also lose water to transpiration through root take up. The surface and subsurface stores will both potentially act as buffers to storm reaction after dry periods when the terrace has drained (Gardner and Jenkins, 1995).

These features combine to ensure that the hydrological systems represented by the model are dynamic environments, especially during storms. However, although the routing of water, the rate of flow, the amount of water in storage and the time therein are complex, interrelated and difficult to quantify on the hillside scale, the local water budget for individual khet terraces remains paradoxically simple at the scale relevant to this study. This observation offers the potential to capture and understand the apparent complexity through the development of a relatively simple conceptual model to represent individual terraces. The emergent complexity at the hillslope scale can then be examined by determining interactions with adjacent terraces in the immediate terrace subsystem, so as to build a replication of processes on the whole hillside.

The description above provides a mass conservation formulation that on a single terrace accounts for inputs from irrigation flow, rainfall and return flow and losses from evapotranspiration, seepage and surface drainage. Experimentation using a prototype model suggested that in terms of the typical rates of these inputs and outputs, it would be expected that changes in local water storage would respond more sensitively to rainfall and surface inflows and outflows, than to subsurface fluxes or variations in evapotranspiration. A pilot study was undertaken to assess this hypothesis.

The pilot study data provided fresh understanding as to the operation of the khet system regarding the relative importance of the components of the surface hydrology system, confirming which processes were the most crucial to define through detailed field study. Process rates were quantified and suggested that at rates typical of the Likhu catchment evapotranspiration, seepage and return flow (when multiplied by representative terrace areas) were indeed of much lower magnitude and thus of less importance than rainfall and irrigation input, thus simplifying both the theoretical explanation of terrace behaviour and field measurement of these process.

This is illustrated using the example of evapotranspiration, one of the more complex environmental variables to measure and model. There are several different methods available to gain accurate measurements of this variable (Shaw, 1994), involving precise measurement of several components, as in the Penman-Monteith equation (Shaw, 1994). Measurement of all components would be impractical for the KhetFlow Model and in most field situations in Nepal. However, if it can be shown that khet systems are not sensitive to changes in evapotranspiration at the timescale of the model, the duration of a storm, then evapotranspiration can be set to a rate based on measured values for the region without affecting the confidence with which the model predictions are viewed. This determines the accuracy (or scale) at which evapotranspiration needs to be measured in the field (described in Section 4.5).

The relative unimportance of evapotranspiration, seepage and return flow was also the conclusion of the sensitivity analysis, explained in Chapter 5. Consequently, as the flux through the boundary between the soil and surface water stores (i.e. seepage) can be reasonably estimated at the scale required for this research and this was of low value compared to the main process rates, the fluxes within the soil were not included in the model design. Subsurface gains from upslope and losses downslope, especially when combined into a net value, are also unlikely to be of consequence at the scale being considered, during and after storms and subsurface lateral flow rates (again particularly when inflow rates have been offset by outflow rates) were expected to be of even less important than vertical ponded seepage or downslope soil water movement, and thus a tiny fraction of those of the main system drivers. As such, no attempt has been made to include provision for these in the modelling. The soil water store was thus not modelled and the justification for this omission was that process rates relevant to this store are relatively unimportant compared with the major drivers of the system; that the net rate of loss/gain from the surface store to the soil-water store during the important phases of the storm/interstorm cycle to be modelled can be reasonably estimated from field measurements; that these estimates were improved during the calibration exercise explained in chapter 6; and that data for terrace drainage rates during long interstorm periods when flow has ceased can be obtained at the scale required from field data.

The validity of an approach that concentrates almost exclusively on the main process rates, whilst estimating or discounting those of less importance, was affirmed by a further important facet of the system that emerged during sensitivity testing (reported in Chapter 5). There is a need to maintain a balance between water inflow and outflow within each set of terraces or the system breaks down either by drying out or flooding and overtopping. In turn, this dictates that the system operates within a narrow range of process rates. This point is explained in Section 3.4 and analysed in detail in the sensitivity analysis, summarised in Section 5.8.

2.3 Perceptual Model: Terrace Reaction

When seeking to quantify the hypothesis underpinning this research it was thought that the surface hydrology of a terrace could be described by using a mass balance equation and that it was only necessary to gain a comprehensive understanding of processes at the micro scale of one terrace. However, this excludes consideration of the complications introduced by the interaction between terraces and the time lag introduced by cross terrace flow. Preliminary fieldwork and prototype modelling provoked the realisation that understanding the interaction between the terraces as well as understanding the reaction of individual terraces was vital to explaining the hydrological behaviour of khet systems.

Cross terrace flow introduces a time lag into the system which theoretically may be considered as follows. When input rates are constant each terrace in a khet system will attain an equilibrium position (discounting micro processes) where outputs are equal to inputs and there is no change in water volume. The terrace system as a whole will also attain such a position of equilibrium. However, if inputs increase or decrease this equilibrium will be disturbed. If the new rate of input remains constant, after a time lag the system will settle to a new equilibrium, obviously at lower water volumes than previously if input has decreased and at higher volumes if inputs are now higher. If input increases to create an equilibrium depth greater than the terrace capacity, that is terrace depth is greater than the height of the bund (lip), the system will overflow and breakdown.

The interaction between terraces caused by a change in input is best illustrated by considering an increase in the input to the top terrace in a system (effectively, an increase in irrigation water). If input to the top terrace increases then the volume of water in the top terrace will increase. However, there will be a time lag - the flow time across the terrace - before this increase in volume is reflected in increased output. As the increased inflow cascades down the system eventually water volume in all terraces will increase but there will be further time lags introduced by the flow time across each terrace. The time lag across one terrace will probably be quite short but the propagation through all terraces will be longer and more important.

Not all the increased inflow to the top terrace is reflected in increased outflow, some will be retained as increased storage. Thus, increased input to the top terrace will cascade down the system but the increase will lose impact in successive terraces because of increased storage in each. Also, the time lag caused by flow should increase successively down the terrace system because the successive reduction of input volume will provide less impetus.

The increased input to the system caused by rainfall is more complex. Assuming uniform rainfall, there is simultaneous increase in water volume to all terraces in the system which triggers the change in equilibrium described above. In each terrace there will again be a time lag until the increase in water volume is reflected in increased outflow, the time lag will vary within the terrace, depending on how close to the outlet each drop falls. Once outflow has increased, there is the same interaction between terraces as when irrigation inflow is increased but each terrace is being affected, at different rates, by all terraces above and is, in turn, affecting all terraces below, also at different rates.

The time lag until a system attains a new equilibrium will also be affected by crop stage (more advanced stage forming a greater barrier to flow); clod height (recent ploughing and shallow water forming a greater barrier to flow) and the relative positioning of inflow and outflow points (which could lengthen cross flow) and provision for this was built into the KhetFlow model design in the manner described in Section 2.6.

2.4 Conceptual Model – Stores and Transfers

As described above, a numerical model representing the surface hydrology of hillslope Khet systems can be constructed by linking together a network of simple, ‘unit’ models that account for variations in flow and storage at the terrace scale. The behaviour of these individual units can be represented by coupling and solving a system of continuity and flow equations for each terrace at the relevant scale. An abstracted form of this core model unit is presented graphically in Figure 2.1.

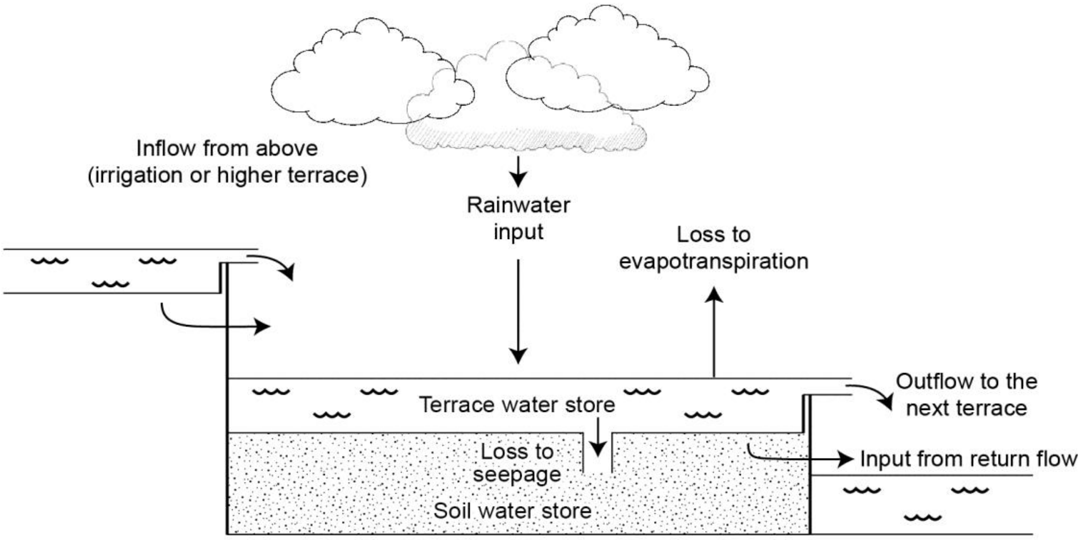


Figure 2.1 Conceptual Model of Water Balance on a Single Terrace

The change in surface storage in any one terrace can thus be represented by the continuity equation (Equation 2.1):

$$\frac{dSt}{dt} = \frac{(Qin + R + K2) - (E + K1 + Qout)}{dt} \qquad [2.1]$$

where,

dSt = Change in storage (l/min)
dt = Change in time (min)

Qin = Surface water inflow from above the terrace or irrigation canal (l/min)
Qout = Surface water outflow to terraces below or out of the system (l/min)

R = Rainfall input (ml/min/m^2)
E = Evapotranspiration loss (ml/min/m^2)
K1 = Seepage loss (ml/min/m^2)
K2 = Subsurface return flow input (ml/min/m^2)

Notes: 1. Rainfall converted from mm

2. Units selected to reflect the scale of the processes and for ease of use in the operation of the model.

The change in surface water storage over time is therefore determined by iterating the calculation equation 2.1 at a given time interval (here taken as one minute), accounting for the various inflows and outflows.

The surface inflow and outflow from the terrace unit in equation 2.1. are then defined in terms of the water storage representing these flows using calibrated stage-discharge relationships. This was achieved by installing uniformly constructed metal inflow and outflow channels on the terraces and considering them as weirs. In the field, the outlets from terraces are mostly roughly rectangular shaped gaps cut in the terrace bund (lip). Their size varies dependent on terrace structure, which is in turn dependent on the need to regulate water flow through the system. Terrace gaps of 5 to 15 cm deep, 10 to 30 cm wide with a base height (height between the soil surface and the base of the outlet) of zero to 5cm are usual. Channel length between the terraces is usually less than 30 cm and, whilst not all natural flow conduits are uniform in shape (or even rectangular), all are effectively a short channel between two stores of water. As such, if the channel shape and base height are regularised and it is ensured that all the water flowing from the terrace flows through such channels then a stage/discharge relationship can be established and the discharge rate determined from depth.

It was not possible to construct the metal channels with sufficient rigour to allow standard weir formula to be used to calculate discharge (for 90˚ weirs of $Q = K \tan^{(90/2)} H\wedge^{5/2}$ (Shaw, 1994)) as the flow length was too short to allow measurements to be taken after turbulent flow had calmed to uniform depth. Depth was thus translated to discharge by calibrating the channels; the method by which this was achieved is described in Section 4.3. Initially, V-shaped weirs were used and calibration provided a rating curve described by equation 2.2.

$$Y = 0.0033X^{2.59} \qquad [2.2]$$

where,

Y = Discharge (l/min)
X = Flow Height (mm)

During fieldwork, all water flowing from the terrace exited though one of these V-shaped weirs, apart from one application when a U-shape was cut into the bund. In theoretical usage of the model described in Chapters 5 and 8, water is assumed to flow through U-shaped weirs as both fieldwork and theoretical modelling showed this to be correct (indeed, that use of V-shaped weirs caused terrace breakdown). For U-shaped weirs calibration provided the rating curve described by equation 2.3.

$$Y = 1.413X^{1.2086} \qquad [2.3]$$

where,

Y = Discharge (l/min)
X = Flow Height (mm)

The model has the facility to switch transfer equations between that representing a V-shaped weir and that representing a U-shaped weir. Each is deployed as appropriate.

2.5 Conceptual Model: Khet Terrace Subsystems

The model seeks to simplify the complex interactions at the hillslope scale by first quantifying the processes at the terrace scale, then determining interactions with adjacent terraces so as to build a replication of processes in terrace subsystems, before providing surface hydrology observation, based on model prediction, for the whole hillside.

The KhetFlow model operates at the scale of khet terrace subsystems and the development, calibration and validation of the model are focused at that scale. In Chapter 8, the interaction between subsystems is considered and predictions and observations made at the hillside scale. Khet subsystems are described as the series of interlinked khet terraces bounded vertically on the hillside between two irrigation canals and horizontally between barriers through which surface flow is prevented (the latter may be manmade, such as paths or ownership boundaries; or natural boundaries such as streams or rock outcrops). The top terrace of the subsystem receives water from the irrigation canal above; the water flows through the bounded set of terraces and discharges from lowest terrace of the subsystem into the canal below. A linear khet subsystem, highlighting the processes modelled in this study, is illustrated in Figure 2.2. Terrace subsystems are positioned on the hillside as shown in Figure 2.3.

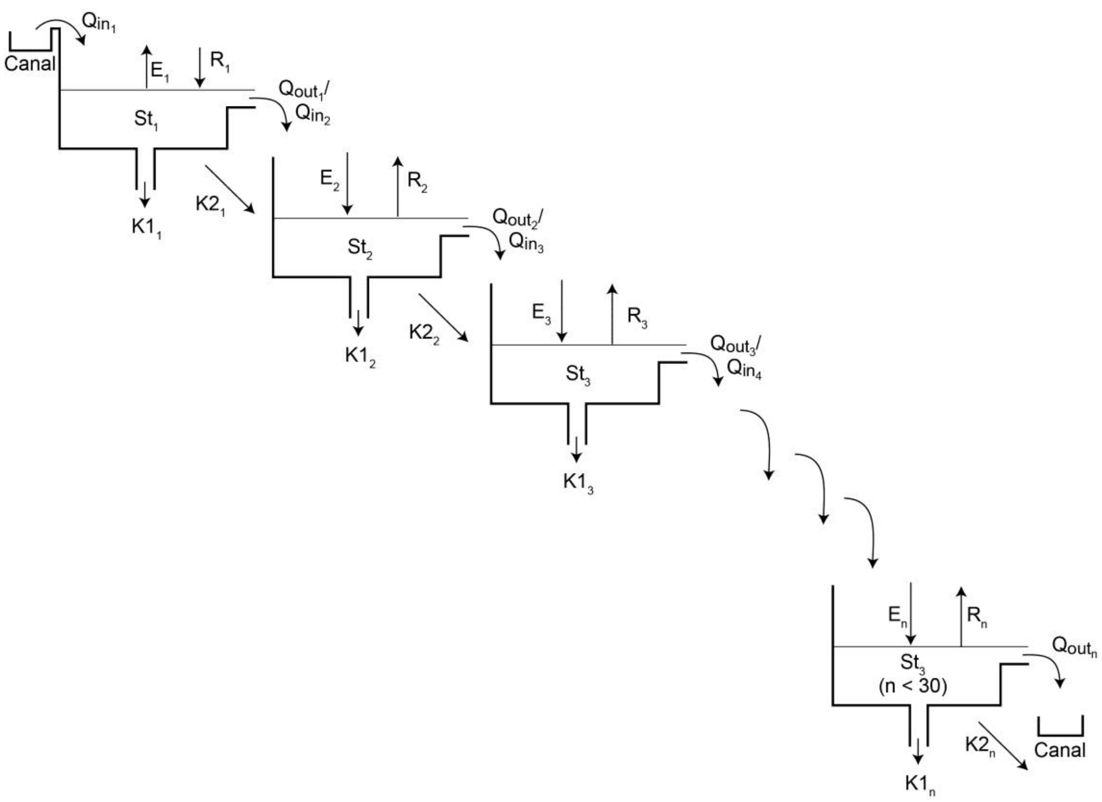


Figure 2.2 Representation of the Processes Modelled in a Linear Terrace Subsystem

To predict the surface hydrology of each subsystem the model performs repeated calculations of the continuity equation (equation 2.1) for the water balance for each terrace as flows and storage increase and decrease during storms and as the system drains in the aftermath. Changes are recorded for each terrace during each iteration of the model run period as adjustments are made for inputs from rainfall, irrigation canals, return flow and by flow from other terraces; and for losses to seepage, evapotranspiration, discharge to other terraces and discharge out of the system. Once change in storage has been determined for the current iteration period change in outflow can also be determined by applying one of the two transfer equations, equations 2.2 and 2.3.

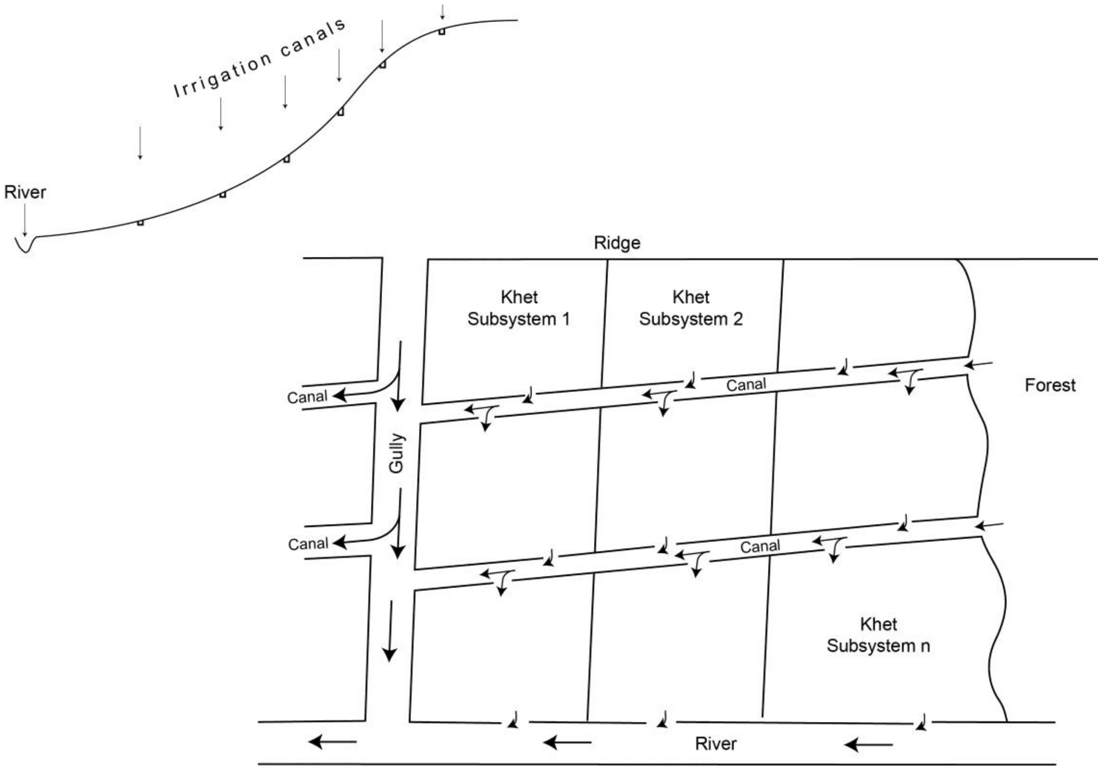


Figure 2.3 Schematic Plan and Profile Views Illustrating the Distribution of Khet Subsystems on the Hillside

The model can be used to replicate flow through more complex systems than the one represented by Figure 2.2, such as where terraces receive input from and discharge into more than one other terrace when there are multiple pathways for water to travel through the system. The initial position of the model applications can be determined by the researcher and as such, the model can be used to simulate the reaction of systems to rainfall from dry (and thus calculate the buffering capacity of terraces after they have been drained by long inter-storm intervals), to simulate normal ponded reaction to rainfall and to quantify the importance of the antecedent position of the terraces if frequent storms occur. Experimentation in such circumstances is described in Chapter 8.

The framework on which the model operates is a terrace structure described and input by the user to replicate the structure of terraces in any particular khet subsystem. Data representing processes are then imposed in accordance with a series of rules set into the internal logic of the model to represent the environment and assumptions of the behaviour of the processes in the physical world. These rules can be modified, if required, by conditions set by the user.

The terrace system used in model applications can be fictitious or a replication of a field system. To describe the principle by which processes operate and to perform a sensitivity analysis the initial work with the model reported in this thesis (Chapter 5) was conducted on a linearly linked subsystem of uniformly sized terraces (as depicted in Figure 2.2). Such uniformity would not exist in the field but this served to isolate the sensitivity of individual processes. In Chapters 6 and 7 the model is calibrated and validated against replications of terraces derived from detailed field measurements in the Likhu valley, including detailed measurements of terrace systems during and after storms. In Chapter 8 more complex subsystems are replicated to illustrate how, once the model has been shown to be accurate over the relatively small sections of hillslope represented by khet subsystems, it can be used to better understand the response of terrace systems at the hillslope scale.

The model incorporates two features that were not required by the application in the Likhu Khola as they did not reflect field conditions tested by this research. However, they should be considered before discounting them from the study.

Flow restriction by clods is accounted for in the intrinsic logic of the model. Two thresholds are set in the calculations and water depth has to rise above each before flow across a terrace is considered to be unrestricted by clods. The first threshold is the ‘Minimum Flow Depth’, below which clods are considered to be so restricting that no flow is possible. Between ‘Minimum Flow Depth’ and the second threshold ‘Clod Height’ flow restriction is estimated on an arbitrary sliding scale, related to depth and starting at 0% and reaching 100% when clods become submerged. These variables are rarely used by the model applications, being utilised only to describe the special cases when the terraces are filling from or draining to empty. For field applications replicated by the model for calibration and validation (described in Chapters 6 and 7), terraces contained sufficient water at the start of the application to ensure free flow so clods (which in the ponded conditions in the field breakdown quickly anyway) did not interfere with the conditions being tested. Clod variables were only utilised in the sensitivity analysis when unrealistic situations were modelled to illustrate the boundaries in which the system must operate and when testing the buffering capacity of khet terraces in Chapter 8.

As well as restricting flow and reducing flow velocities, crops are assumed to effectively reduce the terrace area available to storage. This is accounted for in the model by a ‘Crop Stage’ parameter, which can be set to ‘no crop’, ‘maturing crop’ or ‘mature crop’. ‘No crop’ produces a neutral reaction during model application, ‘Maturing crop’ reduces terrace area by 1%, ‘Mature crop’ reduces area by 2%. These figures have been calculated from measurements of the circumference of rice plants at the relevant stage. However, fieldwork for this research was completed at a time when there was no crop in the terrace, so crop stage was not utilised in the calibration and validation. From field observations, crop stage and clod flow restriction are unlikely to greatly influence the system but this remains to be proved by further work.

2.6 Procedural Model

2.6.1 Logical Operation

The KhetFlow Model is designed to simulate the flow and stores of surface water on hillsides converted to rice terracing, during and after rainstorms. The previous sections of this chapter have described the processes modelled. The remaining sections describe the conversion of the conceptual model into procedural computer code, enabling flexible and rapid operation of the model as a simulation tool.

The model is driven by tables containing values representing process rates for each of the variables on the right hand side of Equation 2.1. Each table contains a value for the relevant process rate for each time unit of the overall model run period. By substituting these values in Equation 2.1 the change in storage of the terrace can be calculated for each time unit and as terrace dimensions, including area, are set parameters, change of water storage translates directly into change of water depth.

Each terrace in the hillside system is described by its dimensions, its rank in the system and its linkages. It is a requirement of the model that the terraces are ranked, to allow orderly processing. Ranking is sequential from the top terrace, numbered 1, to the bottom terrace, numbered x where x will be the number of terraces in the system. This is easiest to envisage in a linear system, where terraces are ranked sequentially through the system. The model can also be used to replicate complex terrace systems, where each terrace can receive and discharge water into several others. It is a requirement of the model that water always flows from a terrace with a lower rank number into one of a higher rank number. Linkages and ranking are maintain in a terrace table and in this manner each terrace is 'virtually positioned' on the hillside. The logical processing of data is illustrated in flowchart form in Figure 2.4.

During a model application the model procedures first examine the initial condition of each terrace as given by the variables held on the data tables, then use the transfer equation to calculate the discharge rate (Qout) through each outflow 'weir' from the height of the water flowing through the weir. This provides the start position of the model and the rate of discharge for each terrace during minute 1 (assuming ^t = 1 minute). As the rate of change of each process on the right hand side of the equation for minute 1 has then either been calculated or is available from the data tables, the change in storage during minute 1 of the model application can be calculated for each terrace in turn. The change in storage at the end of minute 1 is then used to calculate change in the depth of water in the terrace during that minute, which in turn will be reflected in change in the height of water through the outflow(s).

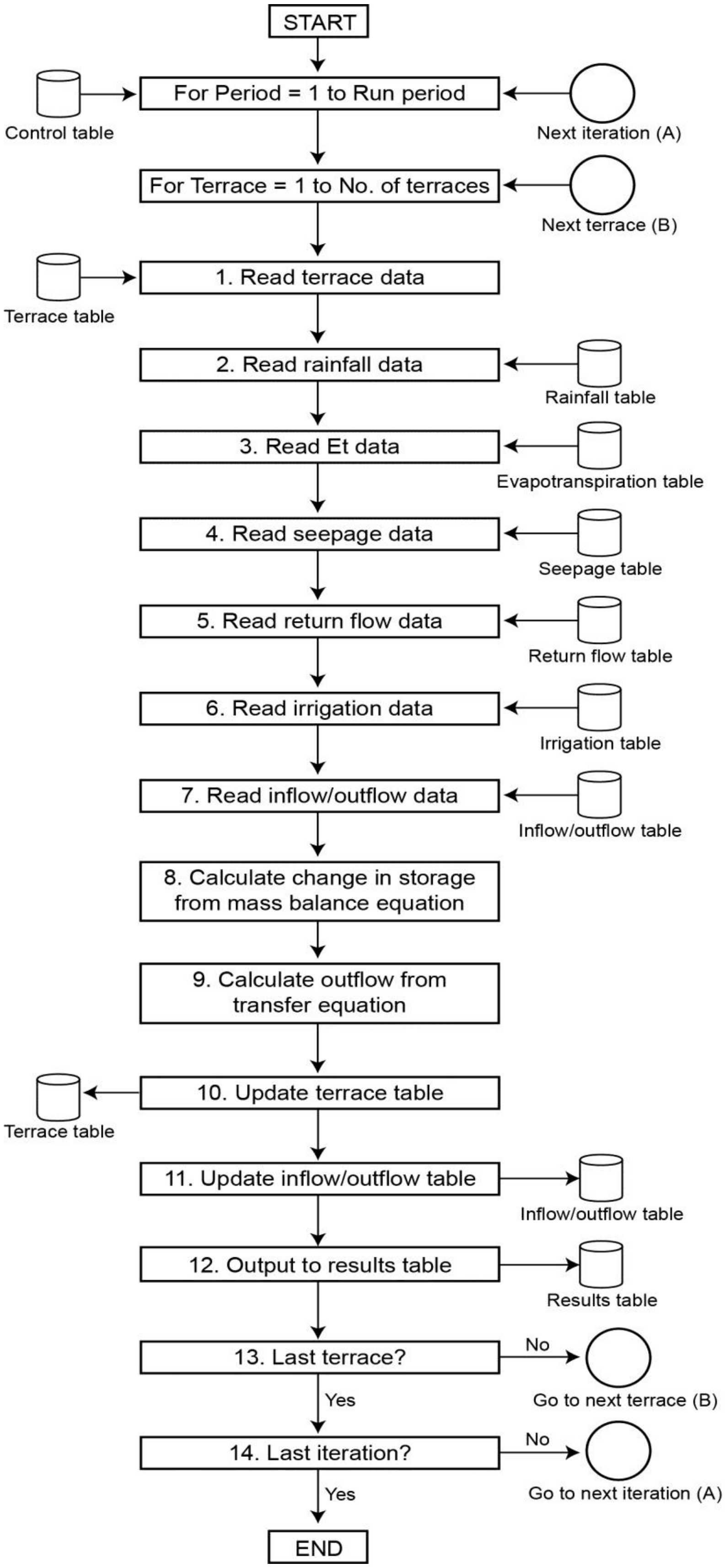


Figure 2.4 Flowchart Showing Logical Processing of Data by the KhetFlow Model

The transfer equation is then again utilised to calculate the change in discharge rate from each weir during minute 1, taking into account that there may be more than one outflow from the terrace and that discharge rates from each might vary because individual outflows might be of different size and at different heights above the terrace floor. The new discharge rate of each outflow weir is stored to be applied during minute 2. When all terraces have been processed for minute 1 the model records the position of all variables then discards the process rates applied during minute 1, replacing them with new rates either calculated or obtained from data tables. The process is then repeated for the next minute and subsequently each minute of the model run.

It is important that the discharge for each individual outflow is maintained separately as outflows may feed into different terraces. In this way the integrity of water routing through the system is maintained and the correct rate of discharge is applied to each pathway.

2.6.2 Data Tables

The KhetFlow Model is a Visual Basic program that manipulates data held in nine tables in an Access database named "KhetFlowDatabase". Each model application utilises the nine data tables. Seven of these tables contain primary data that describe the physical characteristics of the khet system and the processes that act on it. One table is required for data that control the operation of the model and a final table is allocated to capture the results of model applications. The nine tables are:

Two tables to describe the physical characteristics of the terrace/hillslope system:

KhetFlow Terrace Data
KhetFlow Outflow Data

Five tables contain data representing process rates:

KhetFlow Rainfall Data
KhetFlow Irrigation Data
KhetFlow Evapotranspiration Data
KhetFlow Seepage Data
KhetFlow Return Flow Data

The model operation is controlled by:

KhetFlow Control Data

The model also requires that a skeleton table (a table with fields defined but containing no records) be present to receive the results reported by the model:

KhetFlow Results

A detailed description of the operation of the model and the individual fields in the tables is provided in Appendix 3. The flowchart presented as Figure 2.4 illustrates the relationships between the tables and Section 4.8 describes how the model output is compared to field data.

2.6.3 Manipulation of Data for Different Model Applications

The design of the model and the way in which data are presented to it allows considerable operational flexibility. This is required because the model is applied in many different circumstances. It is used as a tool to isolate the importance of individual processes; to reflect different situations in the field, to calibrate and validate the model; and finally to speculate as to what might happen in changed circumstances. This means that it is necessary to apply the model to different hillside systems and in circumstances when data are sometimes incomplete. Flexibility is provided by allowing straightforward data manipulation, both regarding data representing the terrace environment and changes in the strength of processes operating on that environment.

The model is controlled from the Visual Basic screen shown in Figure 2.5, which interacts with the Access tables introduced above. Appendix 3 describes the operation of this in detail.

The terrace environment can be changed by altering the structure of the khetland system within the model. The model is applied to different khetland systems in this study, ranging from isolated terraces to complex hillslope simulations. The terrace environment is presented to the model in the tables Khetflow Terrace Data and Khetflow Outflow Data, described above, so when the environment changes these tables must be changed. Rather than resetting the fields within these tables each time the environment is changed, alterations are effected by creating different tables to describe each environment and copying these in to the model as required, using Access macros developed for the model.

Similarly, data on the five process files can be changed for different applications or, just as importantly, the same data can be easily applied to different environments. Alternatively, process rates are set as a default constant on the Visual Basic form, shown in Figure 2.5.

Flexibility is built into the model in the manner in which process variables are represented. The processes involved are complex and quantifying the rate of each is sometimes difficult. The model has been designed so that the user can decide the appropriate complexity necessary for each process, depending on the requirements of the research programme. This is achieved by, for modelling purposes, holding the data in the five process tables (rainfall, evapotranspiration, seepage, return flow and irrigation inflow) in the format of the rate, per minute of the application, at which each process changes the amount of water in storage in the terraces. For each iteration of the model, each time the model processes a terrace it reads these tables to retrieve the prevailing rate. By holding the data for each process in this way the model can manipulate the data in a simple manner and the complexity of each process is transferred to the point at which the process tables are created, before the model application starts.

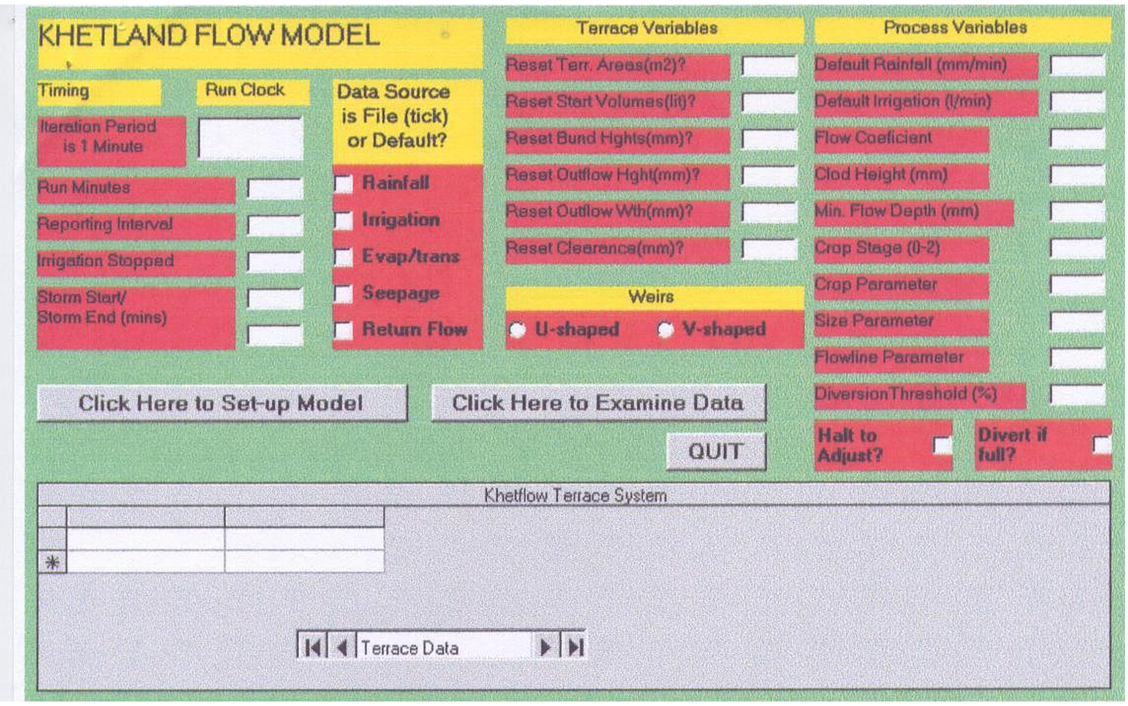


Figure 2.5 Control Form for the KhetFlow Model

The user can thus select a level of complexity appropriate to the importance of the process in a particular application. For instance, evapotranspiration is a complex process that can be difficult to quantify. It may be that in an application where the model is being calibrated against field data all variables to satisfy calculation of the Penman-Monteith equation (Shaw, 1994) are available and it was appropriate to the scale being modelled to apply them (this is not the case in any applications associated with this thesis but it is mentioned here to illustrate the flexibility of the model). If so, the evapotranspiration rate can be calculated or estimated for each minute of the application and input to the Khetflow Evapotranspiration Data table, to be then accessed by the model. At the other extreme, if it was appropriate to the scale being modelled that evapotranspiration be set as a constant (as was decided for this research) that can also be done simply by changing the values in the evapotranspiration table.

The process files thus contain the results of previous determinations of the process rates. In the first applications of the model, when the sensitivity of each variable is being assessed, most of the processes are set to constant rates for the duration of the model application in order to isolate individual variables. As applications become more complex, the process rates are varied, for example to reflect changes in irrigation inflow or rainfall intensity changes during a storm. By holding the data in the manner described above the underlying rate of each individual process can be quantified by simple or complex means before the model is put into operation, leaving the model to calculate the net result of the processes. Additionally, processes may interact with each other during storms. The model can be applied to reflect these interactions during the operation of the model, for example reducing evaporation when it is raining, either by adjusting the data beforehand or, if more complex interactions are required, by small programming changes within the model itself.

The design of the model and the format in which data are held thus allows relatively easy manipulation of the model environment and the processes that operate on it. It allows each application to be quickly repeated as often as the user requires with minor or major modifications to individual variables. This can simulate changes to the environment, processes or simply the variables that control the application to run the model for longer or shorter periods. This flexibility made possible several hundred different applications of the model required to complete this research.

2.7 Summary

The chapter has described the perceptual, conceptual and procedural aspects of the KhetFlow model, in accordance with the stages of development outlined by Beven (2012). The dominant processes were identified during the perceptual stage before a quantitative explanation of the water stores and transfers was provided by the conceptual model. The detailed logic and operation of the model have been explained, together with the structure of the data tables holding information describing the terraces and the processes that operate on it, in the procedural model.

The scale at which the KhetFlow model operates, to simulate the surface hydrological behaviour of khet subsystems, has also been described. However, this does not provide the complete picture and a broader understanding of the khet system environment is required if the systems in which the model is to be deployed are to be fully understood. The hillside context and other aspects of the khet system environment are considered in more detail in the chapter following.

Chapter 3: Modelling Context: Environment and Literature Review

3.1 Introduction

The KhetFlow model was developed for the specific purpose of understanding the surface hydrology of khet terrace hillslopes. However, it is important when defining the model to explain the physical environment of the hillside on which it is deployed, particularly the interaction between terrace subsystems, as the context so provided is fundamental to the modelling of these systems. This chapter first considers the distribution of khet subsystems on the hillside and the linkages between them (Section 3.2), and then describes the manner in which the hillside is divided vertically and why it is so important to understand this (Section 3.3). It continues by explaining the importance of maintain a balance in the water budget for each subsystem (Section 3.4). Taking into consideration the structure of khet systems described and a review of literature, the research is placed in wider context and the use of this particular model in this research is justified in Section 3.5. Consideration of the modelling environment is concluded by describing the physical environment and climate in the area where the research was conducted in Sections 3.6 and 3.7.

3.2 Distribution of Khet Terrace Subsystems

In Nepal, population increase has driven the requirement for more cultivated land and typically cultivation has started with the conversion of the lower, flatter and more easily accessible slopes on the valley bottoms to khetland. It is not unusual to see valley floors completely covered with such fields, some over 50 metres square. Areas higher in the catchment that are more difficult to manage have traditionally been reserved for bariland but economic pressure has also resulted in the conversion of some bariland to khetland (Gardner and Jenkins, 1995). In such places slope angle reduces the size of khet fields and introduces irregular shapes, as dictated by slope contours. Fields can be on the micro scale, sometimes only stretching a few metres along the contour and only 1 metre in width. Figures 3.1 to 3.4 illustrate typical khet systems and variety in their structure. Figure 3.1 shows farmers planting rice on larger riverside terraces in the Likhu Valley; Figure 3.2 illustrates smaller terraces higher in the Likhu catchment; Figure 3.3 shows a small khet system being planted after ploughing and Figure 3.4 illustrates the potential vast magnitude of hillslope khetland development, if conditions allow.

Khet hillslopes are in turn divided into subsystems, always vertically and usually horizontally as well. Horizontally, barriers are often created naturally by gullies, streams or elevated rock; or are manmade, such as paths and ownership boundaries (land holdings are often small, more than 50% being less than 0.5 ha (Central Bureaux of Statistics, 1999) and neighbouring farmers will not share water, which can be scarce outside the monsoon season). More important are vertical divisions, necessary because the consequence of not draining away excess water is terrace overflow and instability. Khet systems rarely extend to more than thirty ‘drops’ between streams or irrigation canals (see Section 3.3 below) and where they do it is almost always because local topography does not allow construction of a canal to drain away the excess water.

3.3 Vertical Division of Khet Terrace Subsystems

The perception that vertical division of khet systems was fundamentally necessary (as opposed to being a feature of local belief or design) was derived from observation and the simulations of a prototype model, which predicted terrace overflow and instability in even modest monsoon storms. Interviews in the field conformed to this assertion. Farmers stated that hillslopes were divided by irrigation canals and/or natural streams and gullies to prevent breakdown of the terraces, which would occur if excess water was not drained from the khet system at regular intervals. Irrigation canals would thus seem to have a secondary, important function, to shed excess storm water from the systems. Whilst in Nepal, supplementary field research was conducted to investigate this, comprising a simple count of the number of terraces in each terrace sequence on several hillsides to test the number of drops between irrigation waterways.

Table 3.1 details the size of typical khet terrace sub-systems. Most of the terrace sub-systems counted were around the Likhu fieldsite but the exercise was repeated down a profile of the larger khet hillslopes of the Modi Khola valley (Figure 3.4), approximately 300 kilometres away. A total of 116 terrace sub-systems in 27 sequences (or profiles) on 5 different hillslopes were surveyed in this way. Table 3.1 records that on four of the hillslopes only 1 sub-system had more than 30 terrace levels, each explained by local terrain such as rock structures that did not allow construction of canals, and there were no sub-systems with more than 36 levels. The anomaly was the West Dee hillslope (west bank of the Dee Khola, a tributary of the Likhu Khola), where 9 of the 32 terrace sub-systems included more than 30 levels and 1 had 60 terrace drops. However, this was again explained by local terrain.

The Dee Khola is an incised tributary of the Likhu Khola and cultivation of the steep slopes of its west bank is marginal. Terraces in many places were consequently small and narrow and in many instances, particularly in the sequence of 60 terraces, only a metre or so wide and 2 to 3 metres in length. The farmers here have decided that, despite the difficulties (imagine, for instance, trying to plough such land using the customary method of water buffalo drawn plough), it was economic to farm this area. However, hillslope morphology was such that it would be impossible to construct an optimum canal system on such terrain.

It was important to test the hypothesis that vertical division of khet systems was fundamentally necessary in the Modi Khola valley because of the scale of the khet systems there and because they are in a different region of Nepal. The Modi is a deeply incised river close to the High Himalaya, flowing alongside the trekking route to the Annapurna Sanctuary. In the Ghandruk area for several kilometers along the valley side there are khet hillslopes that include several hundred ‘drops’ that amount to over 1 km total relief (Figure 3.4). Investigations in the Modi Khola were also important because it was approximately 300 kms away from the Lhiku study site. If frequent canals are vital to drain water from khet systems (as opposed to being a feature of local belief and design) then they should be present in all large khet sequences.

The profile studied in the Modi Khola valley consisted of 12 terrace sub-systems, totalling 266 terrace ‘drops’ in all (see Table 3.1). With one exception systems ranged from 12 to 29 terraces, with a mean of 20.5 terraces. The anomalous system consisting of 36 levels was, as were the exceptions in the Likhu, dictated by local terrain. This system was situated between two large rock outcrops through which it was not possible to channel water, meaning that an effective irrigation canal could not be constructed. An interview with the farmer confirmed that he would have preferred to incorporate a canal in the system but could not and that, indeed, the system broke down several times a year during rainstorms. He had to spend excessive time repairing his land (though it was still economic for him to keep it in production).

Figure 3.1 Riverside Khet Terraces in the Likhu Khola Valley

Figure 3.2 Terraces Higher in the Likhu Khola Catchment

Figure 3.3 A Small Khet System Being Planted After Ploughing

Figure 3.4 Extensive Khet Systems in the Modi Khola Valley

Table 3.1 Length of terrace sequences (no. of drops) between irrigation canals, streams, etc

East Dee Hillslope (7 sequences)				**Mean 18.7**			
12	28	10	25	25	29	25	
10		18	26	25	24	26	
15		12	10	33	10	16	
11			26	16		8	
			19			16	
						9	
West Dee Hillslope (8 sequences)				**Mean 23.7**			
13	20	39	32	33	31	33	20
29	16	20	20	18	12	12	35
12	16	34	16	60	24	20	
		15	16	23	27		
		17	17	17	25		
			35				
Phurkesalla Site (5 sequences)				**Mean 18.7**			
21	21	21	12	17			
16	16	12	***** 18**	14			
8	7	25	14				
32	22	25					
24	18		*** = Khet PA				
25	25						
House Site (6 sequences)				**Mean 16.5**			
21	26	22	8	8	8		
10	8	17	20	31	***** 23**		
11		14	28	14			
14		12	7	10	*** Includes Khet HB		
23		15	25	8			
29							
8							
Modi Khola Hillslope (1 sequence)				**Mean 20.5**			
14							
15							
19							
22		🟨					
17		Terrace sequences greater than 30 shaded yellow					
24							
12							
21							
29							
36							
15							
17							
25							

3.4 Maintaining a Water Balance in the Khet Subsystems

A constant theme throughout this thesis is that the need to maintain a balance between water inflow and outflow within each terrace sub-system is fundamental to understanding the way the system functions and thus to modelling khet systems. This also became an important control on research design.

This research is only relevant if values applied and tested are comparable with probable field situations. There is, for instance, little to be gained whilst developing and testing the model from applying it in conditions wildly beyond those recorded in the field, or trying to operate the model on terrace configurations that are designed badly and don't function; for instance, becoming drained or constantly overflowing during normal operation. Such situations don't happen in reality. There has to be a general balance between inflows and outflows on each terrace as flow propagates through the khet system for the system to function. Process rates and terrace design have to be such that water successfully flows from the top terrace of the system to that at the bottom. As such, it is unrealistic to apply process rates of such inappropriate scale that the system becomes so out of balance as to be inoperable.

The need for a general balance between water inflow and outflow was suggested during experiments on the prototype model and was evident during many field observations, particularly when irrigation was low. During inter-storm periods when the system was in relative equilibrium, the net of all the minor processes in the whole of the terrace subsystem could not be greater than the difference between the amount of irrigation water entering the top terrace of the system and the amount of water exiting the lowest terrace. Field measurements confirm this and it can be seen from the measurements recorded that, at times of subsystem equilibrium before a storm or when the initial impact has dissipated, there is little difference between the amount water entering the subsystem and that exiting back into the irrigation system.

This characteristic of the system was explored further during the Sensitivity Analysis reported in Chapter 5, which suggested that the range of process rates under which the system is viable is quite narrow and the system can to an extent be regarded as self-regulating. This became the overriding control on research design when using the model for speculative purposes and Chapter 8 describes how a khet system with a configuration that functioned properly had to be designed before the model could be deployed in a speculative manner.

3.5 Literature Review and Justification of Modelling Approach

3.5.1 Introduction

This thesis describes the development and application of a computer model, the KhetFlow Model, to provide greater understanding of the surface hydrological response of khet systems to monsoon storms. A search of literature for papers found none reporting such research for the same purpose. During the past fifteen years researchers have developed water balance models for rice terrace systems for other reasons, particularly to estimate irrigation requirements, though usually at the seasonal/annual timescale. Examples of these are provided but this review mostly concentrates on the current paradigms of hydrological modelling, with reference to how these relate to the Khetflow Model and justifying the modelling approach taken. This research originated as part of RGS/IH/HMGN Project (see Section 1.3), which resulted in several modelling papers considering aquatic nutrient balances in the monsoon season, based on data collected in the same watershed as this research and a brief summary of these is included. No papers seeking to explain the hydrological reaction of rice terraces during storms were found.

3.5.2 Rice Terrace Models

Deployment of modelling techniques to aid research into understanding the interaction of hydrological processes in rice terrace systems is a relatively recent development, most examples date from the last fifteen years or so. Most of those based on water balance equations (as is the KhetFlow Model) are concerned with the prediction of irrigation water requirements in the seasonal or annual timeframe. For instance, Ali et al. (2000) estimate the of total water requirement as well as necessary reservoir releases to replenish the water deficit for double cropping of rice in Pedu, Malaysia; Agrawal et al, (2004) predict daily water levels for rainfed rice in terraces with intermittent ponding in Eastern India; and Khepar et al. (2000) predict water requirements in situations of scarce and intermittent supply in Ludhiana, India. Azhar et al. (1992) model weekly irrigation requirements for lowland rice production in Thailand through a water-balance equation but introduce stochastic methods to provide data for rainfall and evapotranspiration, leading to the suggestion that irrigation supply could be reduced in the rainy season. Somura et al. (2005) are equally inventive, developing a model to estimate irrigation requirements in an area with poor data availability in three provinces in Cambodia by calculating back from rice production at the macro scale. Jun-Feng and Yuan-Lai (2009) believe the more general SWAT (Soil Water Assessment Tool) Model can be successfully adapted to the simulation of water cycling in irrigated paddy fields and describe the principle and method of such deployment.

Hauselt (2007) uses a water balance model to consider irrigation from the opposite point of view, investigating the overuse of water in the Sacremento Valley in California, calculating the amount of excess supply above the physiological requirements of the rice plants but noting that the excess improves the quantity and quality of rice production.

The application of a model closer to the methodology reported in this thesis is explained by Jang et al. (2010). They describe the adaptation of the TR-20 Model, originally developed by the US Agricultural Natural Resources Conservation Service to assist with the evaluation of flood events, for use in Korea. TR-20-RICE was developed to investigate the storm runoff characteristics of a 385-ha watershed in Korea and its accuracy is compared to that of the original TR-20 Model when deployed in the same watershed. Although Jang et al. (2010) are working at the catchment scale they use the TR-20-RICE model to simulate the reaction of rice terraces to storms, as does the KhetFlow Model. They are concerned with predicting the storm hydrograph, though the timeframes modelled are longer than is considered in this thesis and they are concerned with the river hydrograph, not that of individual terraces. Jang et al. (2010) report that the adapted model is more accurate than the original in predicting total runoff volume, peak discharge and time-to-peak and, as is relevant to this thesis, note that the improved model was more accurate because it accounted for terrace flooding, without commenting further.

The RGS/IH/HMGN Project was undertaken in the Likhu Khola Valley. The project was multi-disciplinary and resulted in several papers describing the modelling of nutrient balances in the same sub-catchments used for the fieldwork for this research. Collins et al. (1999) describe nitrogen leaching from sub-catchments in the Middle Hills using the INCA model; Collins et al. (1998) describe a GIS framework for modelling nitrogen leaching from agricultural areas and Collins and Jenkins (1995) consider the impact of agricultural land use on stream chemistry. All are based on data gathered in adjacent sub-catchments to those used for this thesis but there is little overlap to the research report here. However, in Collins et al. (1998) it is noted that the management of irrigation water in these systems is complex and they consequently omit explicit consideration of hillslope hydrology and flow routing from their modelling.

3.5.3 Model Limitations and Justification for using a Model in this Research

Beven (2001) suggests that the main reason for the use of models in hydrology is the limitations of hydrological measurement techniques and that, as we have only a limited range of measurement techniques and a limited range of measurements in space and time we need a means of extrapolating from those that are available. Almost all commentators accept the benefits models allow when speculating as to “What if…”. There have been many reviews of models and the modelling process, for example, Wainwright and Mulligan (2004); Beven (2012); Baird and Wilby (1999). All agree that models can be of extensive use in hydrological research but also that there are limitations to that use. The primary limitations currently imposed on model design were summarised by Beven (2001) under five headings; Nonlinearity, Scale, Equifinality, Uniqueness and Uncertainty. Discussions on the subject tend to refer to these points in some form or other but it may be that a more encompassing general assessment could be summed up as a lack of field data and the failure to understand and replicate process variation and interrelationships at a sufficiently detailed spatial and temporal scale. It perhaps reduces to good research design and ensuring that the model methodology decided upon fulfils the stated aims of any particular research; that an appropriate model is deployed in an appropriate manner to answer the question at hand.

The research reported in this thesis aims to better understand surface hydrological processes on khet hillslopes during and after monsoon storms. It became evident at an early stage of the research that, because of the highly structured nature of the environment and because it was possible to collect specific empirical data for calibration and validation, the deployment of a model was appropriate. It was also evident that, whilst it may have been possible to utilise existing models, as little prior research had been conducted on this subject it would be advantageous to develop a new model that explicitly described khet systems and the processes acting on them. The disadvantage of using existing models would always be that such models were developed for other purposes and they would have to be retrospectively ‘fitted’ to this research.

The advantages of adopting a modelling approach became apparent as the research methodology evolved, which together with the structure of the environment in which the research was undertaken, mitigate many of the problems of the modelling process and thus improved expectations of accuracy. Three main advantages were perceived:

1. **Simplicity of Core Processes.** Perceptions gained from preliminary work described in Sections 2.2 and 2.3 and the Sensitivity Analysis reported in Chapter 5 revealed the simplicity of the core processes that required

modelling. Both individual terraces and terrace subsystems can be considered as discrete units where the main gains and losses of water can be simply measured at the required scale. The model is based on the continuity and transfer equations, specifically the change in storage of water in individual terraces (as are khet terraces in the field). Whilst there are a number of processes that contribute to this, most complex were shown to be less important at the scale of this research, whilst processes that were more important were easier to quantify.

2. **Well Defined Start and Boundary Conditions.** A further advantage of the situation in which this model is deployed is that, because the terraces are contained units, start and boundary conditions were relatively easy to ascertain. The primary processes operating at the boundary of the terraces are seepage and return flow and it was determined that these are overwhelmed at the scale at which the model operates, so boundary interactions have less impact. The start position of the terraces in the field, before rainfall commenced, was quantified by straightforward measurement, which provided data for calibrating and validating the model. The internal logic by which the terrace system operates, requiring a water balance to be maintained throughout, allowed quantification of an equilibrium position of terrace water depth at constant rates (see Section 5.2) and thus quantified the start position prior to speculative modelling.

3. **Deterministic Mathematics.** It became evident during the research that whilst it was true that the key to understanding khet systems lay in understanding of the behaviour of individual terraces, equally important was the understanding of the interaction between terraces on the hillslope. From a modelling point of view, the major processes (inputs from rainfall and irrigation inflow from above) are relatively easy to quantify in the field, using raingauges and weirs. Much of the complexity lies in the interaction between the terraces but if the individual terrace processes and the fluxes between them can be quantified with reasonable precision then the

deterministic mathematics of the model are simplified and more likely to be accurate.

3.6 Physical Environmental

3.6.1 Environment Overview

The field site for this research was in the Likhu Khola valley in the Middle Hills of Nepal (GR 27˚50’N, 85˚20’E), about 30 km north of the Kathmandu valley. The Likhu Khola (“khola” is the Nepali word for river) is a tributary of the Trisuli drainage system, which flows from the High Himalaya in the Langtang region and eventually into The Ganges. Figure 3.5 shows the research area with the individual khet systems used for research marked (Khet HA, Khet HB and Khet PA). The shaded areas show locations of RGS/IH/HMGN research sites.

Even though it is only 30 km from Kathmandu the Likhu Khola catchment is a relatively remote area. At the time field work was completed there was no road into the valley, the only access being by foot from the edge of the Kathmandu conurbation, a walk of 6 to 8 hours including the negotiation of a 1,600 metre pass through the Sheopuri range of hills. All equipment had to be carried to the research site, by researchers or by porters, which created obvious logistical problems. The Likhu was chosen rather than the more accessible Kathmandu valley because of existing infrastructure and goodwill from previous research projects. This research was originally conceived as a supplementary extension to the RGS/IH/HMGN project 'Water, Erosion and Land Management' (Gardner and Jenkins, 1995), which had selected the catchment as “typical” and therefore representative of The Middle Hills in terms of population and the wide range of land use systems, including use of chemical fertilisers, recent conversion of bari land to khet land and the presence of several different cultural groups within the farming community. Having prior local knowledge and being able to take advantage of the infrastructure and goodwill remaining gave advantages that outweighed the problem of logistics. This included free use of the project hut for accommodation, in-situ raingauges, the goodwill of local farmers on whose land the work would be completed and, most importantly, the ownership of the four terrace khet system (Khet HA) used to calibrate the model. Ownership of these terraces allowed full control of their management. This gave the freedom to manipulate the terraces according to the research requirements, a privilege unlikely on land on which farmers were growing their own cash or subsistence crop.

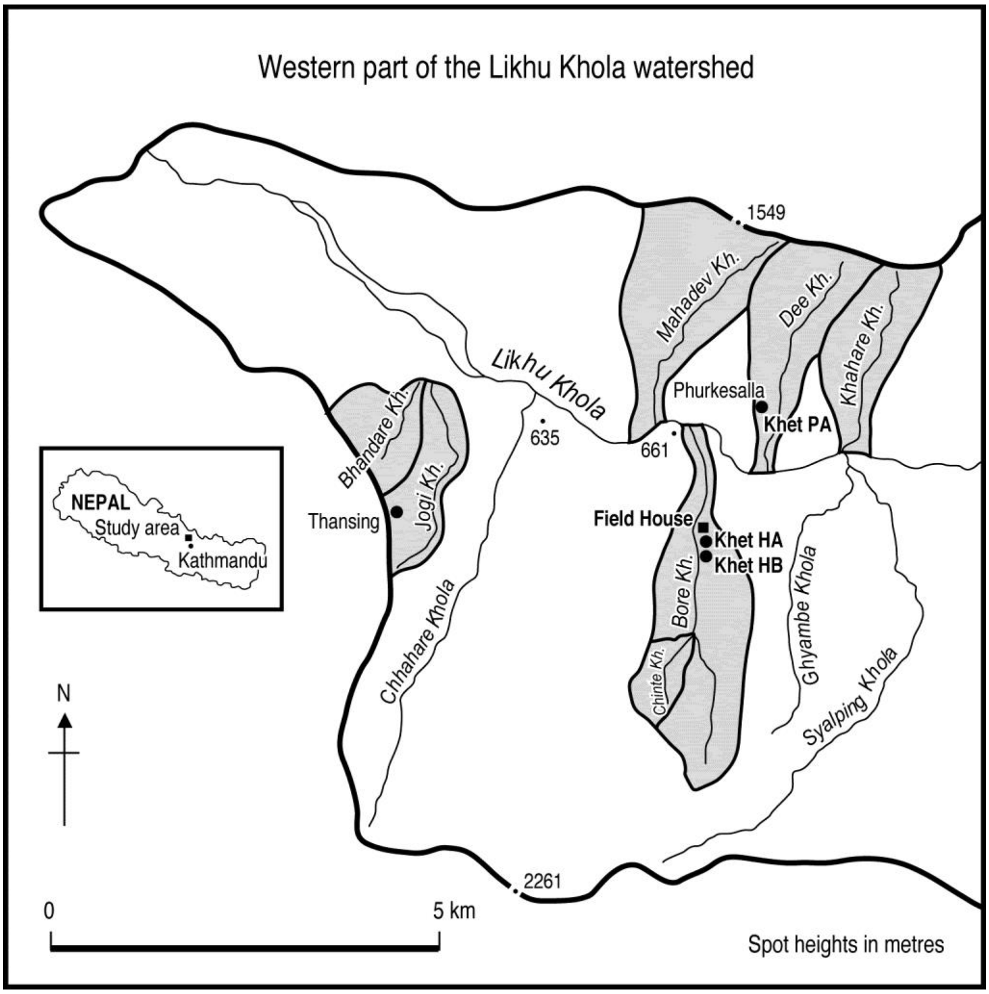


Figure 3.5 Research Area.

Khet HA and HB were located in the Bore subcatchment; Khet PA was located in the Dee subcatchment, both shown on Figure 3.5. Table 3.2 summarises the subcatchment characteristics.

Table 3.2 Summary of Study Subcatchment Characteristics

Catchment	Area (km^2)	Elevation Range (m)	Aspect	% Forest	% Cultivated Land	% Grassland
Bore	4,23	700-1983	north	60.32	38.50	1.18
Dee	2.64	710-1550	south	15.38	58.99	25.63

The following description of the study environment is summarised from the RGS/IH/HMGN project report (Gardner and Jenkins, 1995).

3.6.2 Hillslope Morphology

The Bore subcatchment has the greater relative relief at 1283m and this is reflected in the land use pattern, the higher and steeper slopes in the headwaters being forested, although this is protected second or third generation rather than natural forest. The south-facing Dee subcatchments had maximum elevations at the watershed of 1550m.

The overall morphology of the subcatchments is dominated by naturally formed terraces, predominantly erosional in origin, and cut into the bedrock. They range from altitudes of over 1400m and extend down to the local base level. The terraces, present in both the main Likhu valley and the subcatchments, give rise to the stepped profile of the valley sides that is characteristic of the Middle Hills. The slope angles of terraces are generally of the order of 5-10 degrees, whilst the frontal edges of these terraces can exceed 50 degrees. The outer lip of the terraces typically exhibits a convex slope form. Because of the formation of tributary stream valleys, the terraces of the Likhu valley now often occur merely as remnant convex spurs on the subcatchment drainage divides. This can be seen in Figures 3.2 and 3.3. Above these morphological terraces the hillslopes comprise steep, long and often concave slope forms that extend to the drainage divides.

3.6.3 Soils

Carson (1992) describes the extreme variability in soils and their properties in Nepal, due to differences in the main soil forming factors. Shah (1995) reflects this in the area nearby when classifying soils in the Jikhu Khola watershed, a valley close to the Likhu Khola, with similar landscape and agricultural practices. Gardner and Jenkins (1995) conducted an extensive soil survey in the Likhu Khola as part of the RGS/IH/HMGN Project and reported the soils here fall into three broad groups, with Cambisols being the most common soil group on the khetlands of concern to this study. These soils were characterised by argillic B horizons of up to 3 metres, which tended to have a loam or silty loam texture. Also of note were the gleyic properties present as a result of the general ponding regime.

Wu and Thornes (1995) detail the impact of the ponding regime on the soils on terraces under khet management, on terraces adjacent to those used in this study. They note that rice cultivation needs irrigation in a six month period that extensively overlaps with the monsoon and which generally results in continual standing water during that period except for a few days after transplanting and a few days before harvesting. Wu and Thornes (1995) report that whilst infiltration in khet soil is briefly increased early in the year, the result of ploughing the terrace for rice planting, this occurs prior to the onset of the monsoon. Once irrigation water is introduced subsequent ponding seals the surface and reduces the infiltration rate dramatically, they quote a range of 1.4×10^{-5} cm/s to 7.7×10^{-5} cm/s. They report that most of the soil profile was saturated soon after the farmer first irrigated and that it remained saturated during the whole of the ponding period. Field results from nearby tensiometers revealed that suction in most of the soil profiles was near to zero. The low infiltration rates are in accord with the conclusion of the pilot study conducted for this work and strengthen the case for concentrating on the main drivers of the system in this study.

3.6.4 Drainage

The hillslopes are drained by a dense network of perennial and seasonal streams. Perennial flows occur in the Likhu river and in the main tributary subcatchments, but many of the small steep channels (ravines) that drain into the tributaries only flow during the monsoon unless they are used as routes for surplus irrigation water or they occur on the north-facing forested slopes, often at the higher elevations, where they are fed by springs.

Overall drainage densities are high, 7.20 km per km^2 in the Dee subcatchment and 5.48 km per km^2 in the Bore subcatchment. Most of the tributaries and their feeder ravines are deeply incised and still downcutting into the landscape. Most of the gullies, which only have natural flows during and immediately after storm events, feed into the ravines. The dense and artificial drainage systems, the irrigation networks, are superimposed upon the natural drainage systems, often taking off water from the main stream channels or from the larger ravines, and ultimately feeding surplus irrigation offtake back into the natural system. Gardner and Jenkins (1995) believed that the drainage system provided by khetland would introduce a substantial delay into the natural hydrological system and would lower potentially high peak discharges during heavy storm events. This facet of khet systems is examined in detail in Chapter 8.

Drainage in the immediate vicinity of the field sites was not complex. Khet PA was representative of a typical khet subsystem, receiving water from the irrigation canal running laterally across the hillslope at the top of the system and draining into a similar irrigation canal at the bottom of the system. Water was prevented from exiting the system laterally by a path on one side and a continuous bund on the other to prevent water flowing to a separate khet system owned by a different farmer (farmers do not share water haphazardly, irrigation rights are negotiated in village community meetings). Khet HB represented the top 7 terraces of another typical khet subsystem, receiving irrigation water into the top terrace and with lateral flows blocked. Khet HA was unusual in that it consisted of only four terraces constructed by a Nepali co-worker on surplus land next to the fieldhouse. Bordered by grass banks and the fieldhouse itself, it received water via a channel cut from a nearby stream and drained into a small gully. A more detailed description of each terrace system is given in Section 4.6, describing field monitoring.

3.7 Climate and Rainfall

Kakani meteorological station, which is the closest meteorological station to the study area, is situated at an altitude of approximately 2050m on the southern watershed of the Likhu Khola. Two datasets of were available from this station to provide useful data to give an overview of the prevailing meteorological conditions in the study area. Table 3.3 provides a monthly breakdown of rainfall (and some climatic) data for 1972-86; Table 3.4 shows annual rainfall data for a longer period, 1962 to 1991, and includes the May to September monsoon period rainfall data for 1981 to 1991.

Table 3.3 shows that mean monthly temperature varies from approximately 8 °C in January to over 18°C in June and July. Temperatures fall to below zero on only a small number of days per year, mostly in January. Mean monthly rainfall peaks in July and August (often between late July and mid-August); approximately 25% of mean annual rainfall (2700mm) occurs in each of these two months, both of which experience rain on average on 26 days of the month. On relatively few days did the rainfall exceed 50 mm (4 days on average in August; 3 in July and 2 in each of June and September). The pattern of monthly rainfall between 1972 and 1986 is reasonably similar from year to year, over 80% of the rain falls between May and September, inclusive. From this record the annual maximum one day rainfall rarely exceeded 160mm or fell below 80mm, but it is very variable between years both in terms of rainfall depth, and the month in which it occurs (given that it is always in the rainy season). An analysis of annual maximum one day rainfalls shows that a rainfall of 75mm has a return period of approximately one year at this site.

Table 3.3 Mean Monthly Meteorological Data for Kakani, 1972-86

Month	Temp ° C	Frost (days)	Rainfall (mm)	Max. 24hr Rain (mm)	Number of Rain Days	Number of Days with > 50mm Rain
January	7.7	8.3	16	9	2	0
February	9.7	2.4	21	11	3	0
March	13.6	0.1	37	22	3	0
April	16.8	0.0	66	21	7	0
May	17.5	0.0	150	29	13	0
June	18.6	0.0	480	82	19	2
July	18.3	0.0	681	94	26	3
August	18.4	0.0	703	81	26	4
September	17.5	0.0	446	69	21	2
October	15.3	1.0	106	38	6	0
November	12.0	1.1	8	6	1	0
December	8.6	2.1	19	14	1	0

Table 3.4 shows that mean annual rainfall over the period 1962 to 1991 was 2804mm, and for 1981-1991 it was 2835mm. Mean May to September rainfall was 2558 mm (1981-91), which represents an average of 91% of the total annual rainfall. The proportion of total rainfall accounted for by the May to September rains varies between 94.5% and 85.9%.

It should be noted that the mean annual rainfall in the Likhu valley is at the lower end of the range of data reported for weather stations throughout Nepal (HMG Nepal, 1994). The annual rainfall total for the Modi Khola valley (shown in Figure 3.4) is usually approximately twice that of the Lihku Khola and this was taken into consideration when selecting representative storms for KhetFlow model applications in Chapters 5 and 8.

Table 3.4 Annual Rainfall Data for Kakani, 1962-1991.

Year	Total Rain (mm)	May-Sept (mm)	May-Sept (% Total)
1962	3501		
1963	3069		
1964	2959		
1965	1791		
1972	3074		
1973	3128		
1975	2958		
1976	2654		
1977	2392		
1978	3241		
1979	1734		
1980	2843		
1981	2375	2050	86.3
1983	2986	2637	88.3
1984	2672	2525	94.5
1985	3288	3022	91.9
1986	3054	2688	88.0
1987	2323	1995	85.9
1988	2775	2506	90.3
1989	3163	2973	94.0
1990	2992	2666	89.1
1991	2718	2520	92.7
1992	2141		
1993	2211		
Note years 1966-71, 1974 and 1982 are missing.			

Chapter 4: Methods

4.1 Introduction

Fieldwork was undertaken to provide data to compare with eventual model predictions. Data were required for each of the components of the continuity equation (Equation 2.1) but in light of the insights gained during the pilot study and work with the prototype model, fieldwork was concentrated on measurement of rainfall, irrigation inflow, inter-terrace flow and change of terrace storage (water volume). Evapotranspiration, seepage and return flow were measured by more simplified means (also conducive to the field situation). Further justification for this and a detailed description of the measurement of each component are given below.

A combination of the remoteness of the research site, the unavailability of sophisticated instrumentation in Nepal and the impracticability of importing high value equipment meant that it was not always possible to use the most precise methods. Consideration had to be given to the relative accuracy required for the purpose of the research and pragmatic decisions had to be made as to choice of equipment. Where appropriate, reasons for the choice of method is given below, together with a justification of the manner in which methods where employed for the purposes of this study.

The prototype model and the pilot study suggested that the key to understanding terrace behaviour lay both in understanding the water balance at the single terrace scale and the interrelationship between linked terraces. During the main field season linearly linked systems of 4, 7 and 18 terraces were monitored. Data regarding the physical characteristics of these terrace systems were acquired by measuring area, depth and the number of inflows and outflows. The pre-storm situation of the terrace systems were given by the field measurement of irrigation inflow (if present), inter-terrace flow and water volume of each terrace. During storms, change of storage and inter-terrace flow were measured for each individual terrace. From these data, storm hydrographs were constructed showing change in volume of individual terraces during and after the storms monitored.

4.2 Measurement of Rainfall

Rainfall was measured by both manual and automatic (tipping bucket) raingauges, the former as a safety measure given the known difficulty of maintaining automatic gauges in remote sites. (Fortunately, the automatic raingauges proved reliable and provided data for all storms reported in this thesis.)

Two automatic raingauges were deployed, each programmed to tip at each 0.2 mm of rainfall, the time of tip being recorded to the nearest second. To provide data for input to the KhetFlow model measurements were combined to provide total mm of rain per minute (the scale at which the model operates) for the duration of the storm. The raingauges were calibrated by introducing a known volume of water over a fixed period of time to quantify the actual rainfall recorded by each ‘tip’, this being 0.185 mm and 0.2 mm respectively for the two gauges. Rainfall totals and intensities recorded by the gauges were adjusted by this calibration. Straight line averaging was employed when rainfall intensity dropped to the extent that no tips were recorded for any one minute during a storm. Readings of total rainfall were taken daily from the manual raingauges.

4.3 Measurement of Water Volume and Inter-terrace Flow

Water volume was calculated by multiplying terrace water depth by terrace area. Terrace water depth was measured by reading from a bamboo pole fixed in the floor of the terrace. The depth of each terrace was sampled in 20 places when each depth measurement post was inserted, the mean of these figures being used to calibrate the post and the water depth to volume calculation. The pole was calibrated with centimetre and 5 mm markings, readings between the 5 mm marks were estimated visually by the person measuring. It was expected that this method would give accuracy to about +/- 3 mm but, as is described below, these measurements proved erratic when compared to measurement of flow depth through the terrace weirs (changes in which should have a 1:1 relationship with changes in water depth).

When calculating water volume from area and depth, inaccuracies would be introduced if terrace sides were not perpendicular and because terrace floors might be uneven. The former is mitigated by the vertical nature of the terrace faces, the farmer ensures terraces are cut vertically to maximise growing area. The relative shallowness of terraces (the depth of the terraces is rarely greater than 15 cm) also mitigated error and, whilst the floor of the terrace could be initially uneven, it tended to be level as saturation and water flow quickly breaks down clods.

Metal 90˚ V-shaped weirs, constructed in workshops in Kathmandu and carried into the Likhu valley, were installed to measure discharge between terraces. Measurement of flow height through these terrace outflows was by steel ruler with 1 mm divisions. The weirs were 35 cm long, 30cm wide and 15 cm deep at the base of the V. Measurement was always made at the same point of the weir at the longitudinal centre, for consistency and to avoid the slope on the water at the very front of the weir. The weirs were pushed into the soil of the bund and mud was packed around the outside to prevent leakage. V-shaped weirs were used as these were expected to give more accurate recordings of the flow between terraces, particularly at low flows (Shaw, 1994). However, during heavier storms, these caused depth increases as water in the terraces ‘backed up’ because the weirs were too restricting. For this reason, prior to the storm event reported on Khet PA (one of the field terrace systems utilised) the weirs had to be removed. These were replaced by U-shaped gaps constructed in each bund and flow across these was calculated from terrace depth readings. This was problematic and, as is described in Chapter 7, possibly introduced errors into field data.

It was not possible to construct the weirs with sufficient rigour to allow standard weir formulas to be used to calculate discharge (for 90˚ weirs of $Q = K \tan^{(90/2)} H^{5/2}$

(Shaw, 1994)) as the weirs were too short to allow measurements to be taken after turbulent flow had calmed to uniform depth. Depth was translated to discharge by calibrating the weirs. Weir calibration of the V-shaped weirs was performed on those installed in Khet HA. Water depth in the weir was recorded. Discharge was timed until a known amount of water had been collected and a discharge amount in litres per minute calculated. This procedure was repeated 4 times for each height calibrated and the mean figure used to plot a rating curve (Figure 4.1). This provided Equation 2.2 to be used as the initial transfer equation to calculate inter-terrace flows and flows in and out of the terrace sub-systems.

To calculate transfer rates in the situation where the U-shaped gaps had been fabricated, a U-shaped weir was constructed and calibrated by the same method as that used for the V-shaped weir. The U-shaped weir was also 35 cm long and 15 cm in depth, with had a width of 20 cm. The calibration curve constructed for this shape of weir is shown in Figure 4.2, which provided the Equation 2.3 to be used as the transfer equation to calculate inter-terrace flows and flows in and out of the terrace sub-systems when U-shaped gaps were utilised.

The sensitivity analysis reported in Chapter 5 supported the field observation that U-shaped inter-terrace gaps better reflected reality and the experimentation with terrace system design reported in Chapter 8 reproduced and illustrated the cause of the terrace overflow and system failure seen in the field when using V-shaped weirs. As is reported in Chapter 8, subsequent speculative modelling then reported uses Equation 2.3 as the transfer equation.

Terrace water depth and the height of the flow of water through the terrace outflows are synonymous if the base of the outflow is level with the floor of the terrace, assuming there is no slope on the water. If the outflow is above the terrace surface the clearance between the terrace floor and the base of the outflow has to be taken into account. Except for Khet PA, field measurements were taken of both terrace water depth and outflow water depth. However, field recording of these was made more difficult because conditions were usually adverse and extreme care had to be taken to obtain accurate measurements. During the rising limb of the hydrograph measurements were taken during, often heavy, rainfall. The gaps (bunds) between the terraces are only designed to be walked on intermittently – the farmer cuts them as thinly as possible to maximise growing area – and these would usually be muddy and slippery. A dearth of daytime rainfall meant that measurements often had to be taken by torchlight during the night.

Because of these difficulties, the readings from the bamboo pole and that calculated by adding weir flow height to weir clearance were often different. Measurements for terrace water depth taken from the bamboo poles were more erratic, possibly because these measurements were usually taken from a distance of several metres from a hand marked pole whereas measurement of weir water depth was from close proximity and with a steel ruler. This being the case, during the modelling phase the decision was taken to use depth as calculated from weir flow height, plus clearance (except for Khet PA where weirs had been removed). Using these figures, field error margins might still have been several millimetres at times but, as is discussed in the Calibration and Validation chapters, acceptable accuracy was attained.

Recordings were taken every 15 or 20 minutes during the rising limb and approximately every hour during the falling limb. Ideally, all terraces in the system should be measured simultaneously in order to take a “snapshot” of the whole system being monitored. Time lags introduce inaccuracies as water would, in effect, “be measured twice”. However, simultaneous measurements were not possible in the field conditions; on the 4 and 7 terrace systems a set of measurements were completed in two to four minutes but it took up to 10 minutes to measure every terrace of the 18 terrace system. Measurement of water volume and inter-terrace flow is illustrated in the step-by-step example described below in Section 4.6.

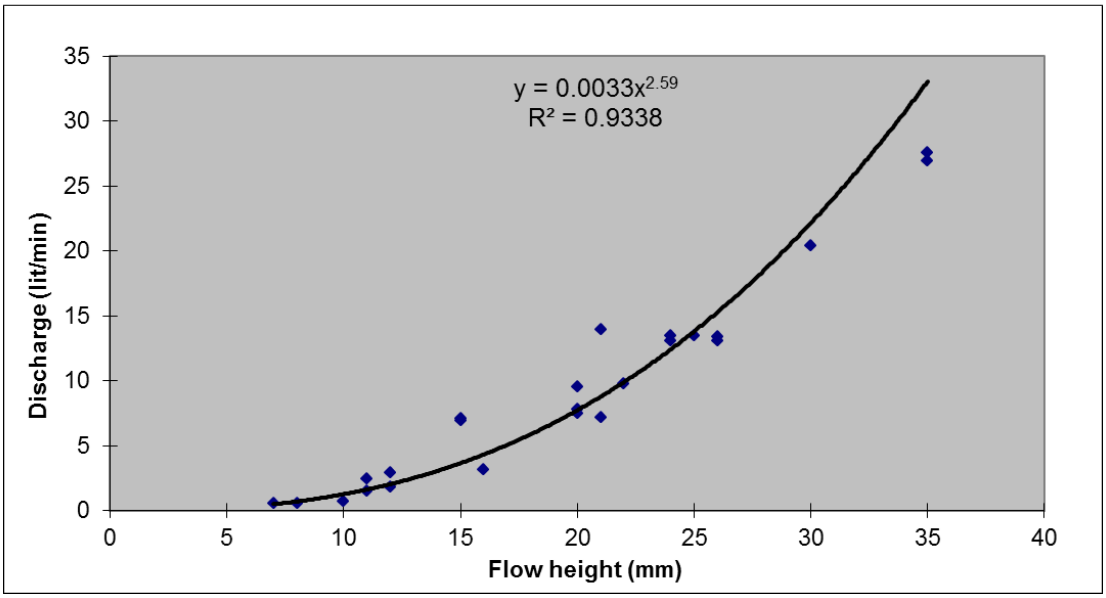


Figure 4.1 Calibration of V-shaped Weirs

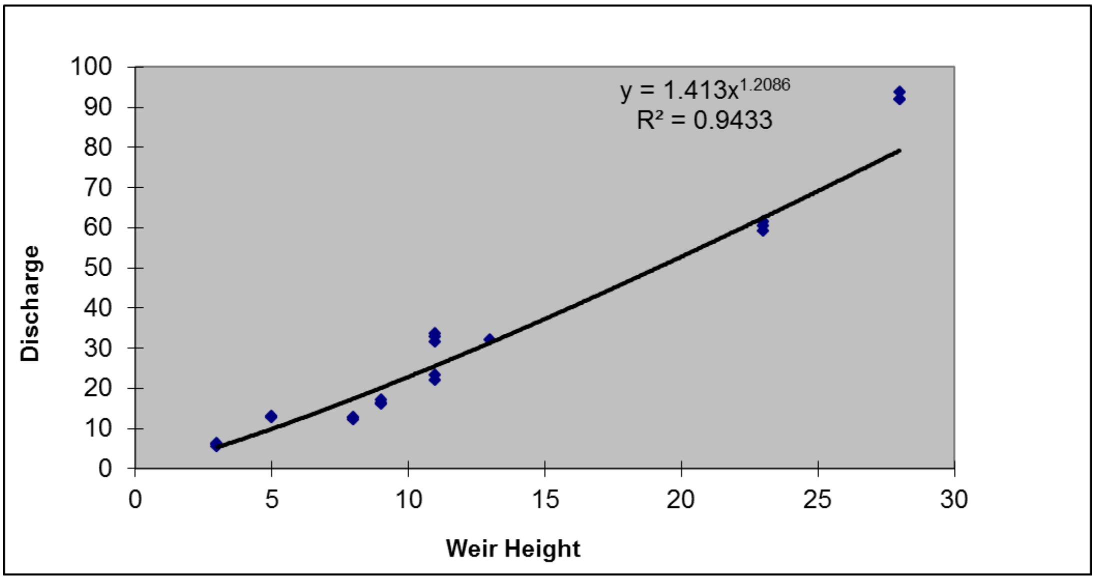


Figure 4.2 Calibration of U-shaped weirs

4.4 Measurement of Terrace Area

It was not practical to import and use sophisticated surveying equipment with which to measure terrace area. The area of each terrace was calculated by measuring the length of the longest axis of the terrace and then taking perpendicular measurements of the width at one metre intervals. These measurements were plotted to scale onto graph paper and area calculated by counting the squares covered and multiplying this figure by the scale.

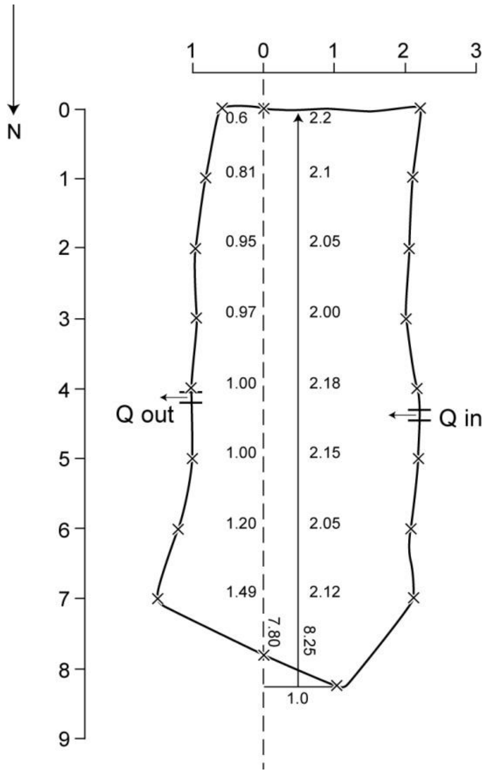


Figure 4.3 Calculation of the Area of Terrace Khet HA4 (measurements in metres)

4.5 Measurement of Evapotranspiration, Seepage and Return Flow

It was impractical in the Likhu Khola catchment to measure these complex processes with the accuracy that would be possible in the UK. However, it was possible to undertake measurements to accuracy suitable to the scale at which the KhetFlow model operates, as is shown in Table 4.4, where relevant process rates are compared. This was justified because measurements of rainfall, irrigation inflow and inter-terrace flow made during the pilot study showed that rates for these processes far exceeded maximum possible rates for evapotanspiration, seepage and return flow, allowing less rigour in the measurement of the latter group of processes, provided that the precision used was of appropriate scale. This was supported by the sensitivity analysis described in Chapter 5, which shows that the net rate of these three processes has to be set within a narrow band of low net loss or the system would break down.

Evaporation was estimated by burying a simple evaporation pan (a large plastic washing up bowl) in a clear area unaffected by overhanging vegetation, with the lip of the bowl at the same level as the ground. For 22 consecutive days water loss was recorded for a known time period (see Table 4.1). Mean water loss was 0.36 mm/hr and the highest figure recorded, on a day when shade temperatures reached 33°C, was a water loss of 1.54 mm/hour. This is expected to be close to the maximum evaporation in the prevailing meteorological conditions and is likely to be significantly higher than during and immediately after a storm, when conditions for evapotranspiration would be less favourable (particularly at night). Table 4.1, also converts evaporation figures to equivalent water loss per hour from terrace HA1 and this is compared to rates of rainfall and irrigation in Table 4.4.

It was not practical in the field to separate return flow from seepage as it was not possible to block return flow. The net loss from the two processes was estimated in a similar way to evaporation, recording depth loss over time. Measurements were taken from each of the HA, HB and PA khet systems that were used for calibration and validation in Chapters 6 and 7. Inflow and outflow was blocked from selected terraces and change in water depth was recorded over the same time period as water loss measurements from the evaporation pan (above); the depth loss due to seepage/return flow being calculated as the overall depth loss minus that from the evaporation pan. Results are presented in Table 4.2. The maximum loss was 1.33 mm per hour from terrace HA1 but four of the six results were less than a third of this and the mean was 0.57 mm per hour. This is compared to rates of rainfall and irrigation in Table 4.4.

Table 4.1 - Evaporation Estimates from Likhu Khola Site

Date	Start	End	Hours	Water Loss ** (mm)	Evaporation per hour from HA1 mm)	Comments
14 July 1995	12:00	18:00	6	4	0.67	Hot and sunny
15 July 1995	06:30	13:00	6.5	4	0.62	Hot and humid
15 July 1995	13:00	06:30 (16/7)	17.5	6	0.34	Afternoon and night
16 July 1995	06:30	12:00	5.5	2	0.36	Overcast, v. humid
16 July 1995	12:00	18:30	6.5	10	1.54	V.hot
16 July 1995	14:00	18:30	4.5	4	0.89	For HA seepage test (v.hot)
18 July 1995	02:00	12:30	10.5	3	0.29	Mostly night
20 July 1995	00:00	10:30	10.5	3	0.29	Mostly night
20 July 1995	10:30	19:00	8.5	6	0.71	For HB seepage test
20 July 1995	19:00	08:15 (21/7)	13.25	7.5	0.57	** Rain
22 July 1995	09:45	14:00	4.25	2	0.47	Hot and humid
22 July 1995	14:00	07:00 (23/7)	17	1	0.06	
23 July 1995	07:00	07:00 (24/7)	24	3	0.13	** Rain
25 July 1995	07:00	19:00	12	3	0.25	
25 July 1995	19:00	06:00 (26/7)	11	0	0.00	Night
26 July 1995	06:00	16:00	10	5	0.50	V.hot
26 July 1995	16:00	09:00 (27/7)	17	0	0.00	** Rain
28 July 1995	13:30	16:00 (29/7)	26.5	2	0.08	For PA seepage test
29 July 2007	16:00	07:00 (30/7)	15	0	0.00	** Rain
30 July 1995	07:00	16:00	9	2.5	0.28	** Rain
31 July 1995	17:00	05:45 (1/8)	12.75	1	0.08	** Rain
01 August 1995	07:00	18:00	11	1.5	0.14	** Rain
02 August 1995	16:00	07:00 (3/8)	15	0	0.00	** Rain
03 August 1995	07:00	15:00	11	4	0.36	V. Hot
Mean					0.36	
** Indicates evaporation net of rainfall measured from an adjacent rainguage						

It was possible to estimate return flow by fixing seepage troughs into the terrace risers. The terrace being measured was filled to a normal depth and the outflow blocked. Water seeping (returning) through the face of the riser and into the troughs (in the terrace below) was collected in sample bottles and the time to collect a known quantity noted. The troughs were 1 metre long and positioned on risers 3.5 metres wide in the case of terrace HA1 and 8 metres wide in the case of terrace HA3.

Table 4.2 Combined Seepage/Return Flow Estimates from Terraces HA, HB and PA

Date	Terrace	Start	End	Hours	Water loss (mm)	Evap. (mm)	Seepage/ Return flow (mm)	Equivalent per hour (mm)
16 July 1995	HA1	14:00	18:30	4.5	10	4	6	1.33
16 July 1995	HA2	14:00	18:30	4.5	6	4	2	0.44
20 July 1995	HB1	10:30	19:00	8.5	12	6	6	0.71
28 July 1995	PA5	13:30	16:00	26.5	8	2	6	0.23
28 July 1995	PA6	13:30	16:00	26.5	9	2	7	0.26
28 July 1995	PA8	13:30	16:00	26.5	13	2	11	0.42
Mean								0.57

Return flow was estimated by calculating an hourly rate of water collection and multiplying this by the width of the riser face. Results are presented in Table 4.3, a mean loss of 0.89 mm per hour with the maximum being a loss of 1.52 mm per hour from terrace HA3. Table 4.4 compares the mean and maximum rates for evaporation, seepage/return flow and return flow with rates of rainfall and irrigation for the events used to calibrate the model in Chapter 6. All the process rates (except irrigation) are shown as mm per hour and then converted to ml/min/m^2, as used by the KhetFlow model. Irrigation is shown as litres per minute input to HA1 and then converted to ml/min/m^2 by dividing by area.

Maximum rates of evapotranspiration, seepage and return flow range from 22 to 26 ml/min/m^2, and mean values from 6 to 15 ml/min/m^2. Maximum rainfall intensity ranged from 185 to 800 ml/min/m^2 and means from 61 to 282 ml/min/m^2. Irrigation varied from 74 ml/min/m^2 (when irrigation was deliberately curtailed) to 834 ml/min/m^2. This illustrates clearly that field measurements of rainfall and irrigation are of much greater magnitude than evaporation, seepage and return flow. It must be emphasised that the purpose of the above is not to provide accurate measurements for these processes but to confirm that estimates used when modelling are approximations of process rates appropriate to the purpose of the KhetFlow Model. However, these figures further support the finding of the pilot study and the contention of the sensitivity analysis reported in Chapter 5, that the net rate of these three processes has to be set within a narrow band of net loss or the system would break down and that this value should be relatively low.

Table 4.3 Return Flow Estimates

		Trough		Hourly Rates		
Date	Terrace	Amount	Time	Trough	Full face	Terrace loss
		(l)	(mins)	(l)	(l)	(mm/hour)
21/07/95	HA1	2	9.58	12.53	43.84	0.65
21/07/95	HA3	1	12.50	4.80	38.40	1.52
22/07/95	HA1	1	4.07	14.74	51.60	0.77
22/07/95	HA3	1	19.26	3.12	24.92	0.98
25/07/95	HA1	1	6.10	9.84	34.43	0.51
Mean						0.89

Table 4.4 represents field confirmation that rainfall and irrigation rates are of much greater magnitude and thus far more important than those for evapotranspiration, seepage and return flow during and in the immediate aftermath of storms, to the extent of approximately an order of magnitude.

Table 4.4 Comparison of Rates of Rainfall, Irrigation, Evaporation, Seepage and Return Flow

Rainfall and Irrigation for Each Storm Event used for Calibration						
	Max rain	Mean rain	Irrigation	Converted to ml/min/ m^2 for comparison (as used in the KhetFlow Model)		
Event	Intensity	Intensity	Peak	Max rain	Mean rain	Irrigation
	mm/hour	mm/hour	l/min	Intensity	intensity	HA1
	**1	**2				
Jul-11	24	7.6	22	400	126	328
Jul-13	0	0	50	0	0	745
Jul-16	11.1	3.7	56	185	61	834
Jul-17	44.4	10.1	5	740	169	74
Jul-30	48	16.9	26	800	282	387
Jul-31	12	3.9	36	200	65	536
Mean and Maximum Rates of Evapotranspiration, Seepage and Return Flow (compare to rainfall and irrigation in three right hand columns above)						
				Converted to ml/min/ m^2 for comparison (as used in the KhetFlow Model)		
					Maximum	Mean
Evapotranspiration – mean 0.36 mm/hr, max. 1.54 mm/hr					26	6
Seepage/Return Flow – mean 0.57 mm/hr, max. 1.33 mm/hr					22	9
Return Flow – mean 0.89 mm/hr, max 1.52 mm/hr					25	15
**1 Max 15 minute period						
**2 Start to finish of main storm						

4.6 Field Monitoring of Terrace Systems

Three terrace systems were monitored, consisting of four, seven and eighteen terraces respectively.

The Khet HA terrace system consisted of four linearly linked terraces. The terraces were all roughly square with water flow between a single inlet and single outlet, each positioned centrally in the bund. The terraces were fed by irrigation water and had no crop or recently ploughed clods to disrupt flow. The system was bounded by a drop into the project field house on one flank and grassland on the other. As discussed later, it was suspected that there was unmonitored run-on into HA4. This small khet system is indicative of the land pressure and economics of rural Nepal. It was constructed on a small piece of land left vacant after the building of the Likhu Khola fieldhouse. Even though it took a considerable amount of physical effort to dig out the four khet fields and it was likely that these would only be available for cultivation for 3 to 5 years (because the fieldhouse and surrounding land were to revert to the community for use as a school at the end of the project), the farmer of the adjacent land considered it economic to convert this 144 square metres to khet.

Khet HB, consisting of seven terraces was also close to the project fieldhouse. The terraces were linearly linked with good internal flow lines, they were fed by irrigation water and had no crop or recently ploughed clods to disrupt flow. The terraces were bounded by drops on each flank, so there was no possibility of run-on and were irregular in shape and in general much smaller than those of Khet HA.

Tables 4.5a, b and c – Khet HA, Khet HB and Khet PA Terrace Areas.

a)

Terrace	Area (m^2)
HA1	67.14
HA2	26.37
HA3	25.34
HA4	24.13

Terrace	Area (m^2)
HB1	42.69
HB2	8.06
HB3	8.51
HB4	12.26
HB5	7.1
HB6	19.54
HB7	24.22

b)

Terrace	Area (m^2)
PA1	22.5
PA2	30.75
PA3	59.5
PA4	20.0
PA5	76.25
PA6	46.5
PA7	16.25
PA8	42.75
PA9	94.5
PA10	88.0
PA11	128.25
PA12	156.75
PA13	172.25
PA14	105.5
PA15	230.0
PA16	88.5
PA17	41.5
PA18	36.75

c)

Khet PA consisted of 18 terraces and was situated on the opposite bank of the Likhu Khola, about 1.5 km distant (see Figure 3.7). The terraces were much larger than those in the other two systems, were linked linearly and were approximately rectangular, though some were of irregular shape. All had good internal flow lines and, even though the rice crop had been planted, flow was not disrupted as the crop was very young and there was no clodding. The system was flanked on one side by a pathway and on the other a continuous bund, separating the terraces from those of other farmers.

For the purpose of monitoring the terraces in each system were numbered sequentially starting at the top. Terrace areas for the three systems are shown in Tables 4.5a, b and c.

4.7 Measurement of Rainfall Events

Eight rainfall and/or irrigation events, each different in character, were measured. Six events were monitored on single terrace systems and two events were monitored on two terrace systems, providing ten discrete events in all. Six were monitored on Khet HA, the four terrace system; three events were monitored on Khet HB, the seven terrace system and one on Khet PA, the eighteen terrace system. Seven of the events were storms and one the release of irrigation water into dry terraces. The magnitude of the storm events varied from 4.8mm to 44.8mm and the duration from 17 minutes to 6 hours 50 minutes. Monitoring periods for the events varied from just under 5 hours to 11 hours.

The events were monitored from the start of rainfall, through the peak of the event and during the falling limb until such time that the system was draining at a constant rate and had reverted to similar levels as the start conditions, or was at or close to a new equilibrium. However, it should be noted that the system is one of dynamic equilibrium and the normal condition is that it is slowly altering towards a new equilibrium position, which may never be attained as the system reacts to a further change. At the start of the event the system may have still been changing to a new equilibrium and at the end of the event, particularly when irrigation levels had been changed by rainfall, this was also likely to be the case.

Table 4.6 summarises the event characteristics and detailed descriptions of the events are given below. From the storm descriptions and the summary table it can be seen that the ten events represent a wide range of rainfall/irrigation events.

The field monitoring results can be viewed in the hydrographs presented with the model calibration and validation in Appendices 1 and 2. These show hydrographs of each terrace monitored for each of the ten discreet storm events. Figures 4.4 a) to d) provide an example of the hydrograph of model output predictions here, showing the reaction of Khet HA to the July 11th storm event, prior to an example of comparing model and field data given in Section 2.8.

Table 4.6 - Storm Characteristics

	Rainfall		Max	Irrigation			Monitoring
Event &	Duration	Magnitude	Intensity	Start	Peak	End	Duration
Terraces	mins	mm	mm/hour	l/min	l/min	l/min	mins
	**1		**2				
Jul-11 HA	208	17	24	0	22	1	256
Jul-13 HA	0	0	0	50	50	50	340
Jul-16 HA	265	10	11.1	10	56	36	520
Jul-17 HA	395	34.4	44.4	0	5	0	660
Jul-17 HB	395	34.4	44.4	0	8	0	660
Jul-19 HB	139	23.9	88.8	0	240	2	460
Jul-30 HA	17	4.8	48	22	26	19	556
Jul-31 HA	175	11.4	12	20	36	22	556
Aug-3 HB	410	45.8	60	0	200	68	460
Aug-3 PA	410	45.8	60	0	186	14	460
**1 Start of first rain to end of last rain - can include dry periods							
**2 Max 15 minute period							

The substantial impact of the onset of rain on the water volume in the terraces can be clearly seen. Terraces fill quickly, even when rainfall is not enhanced by increased irrigation but especially so when that is the case. However, the complexity of system response was illustrated as rapid increases in water volume were not reflected in similarly rapid draining of terraces after rain ceased. Whilst top terraces could attain pre-storm volumes in a couple of hours, it usually took many hours for the terraces lower in the system to drain (depending on the size and number of terraces in a system). This raises questions about the importance of antecedent terrace conditions, in situations where a second monsoon storm follows closely after its predecessor. If terraces have not yet drained from the first storm the reaction to the second (or subsequent) storm will be more severe. This is examined in detail in Chapter 8.

The fieldwork results thus further strengthened the perception that by far the dominant processes during storms were water inputs from rainfall and irrigation.

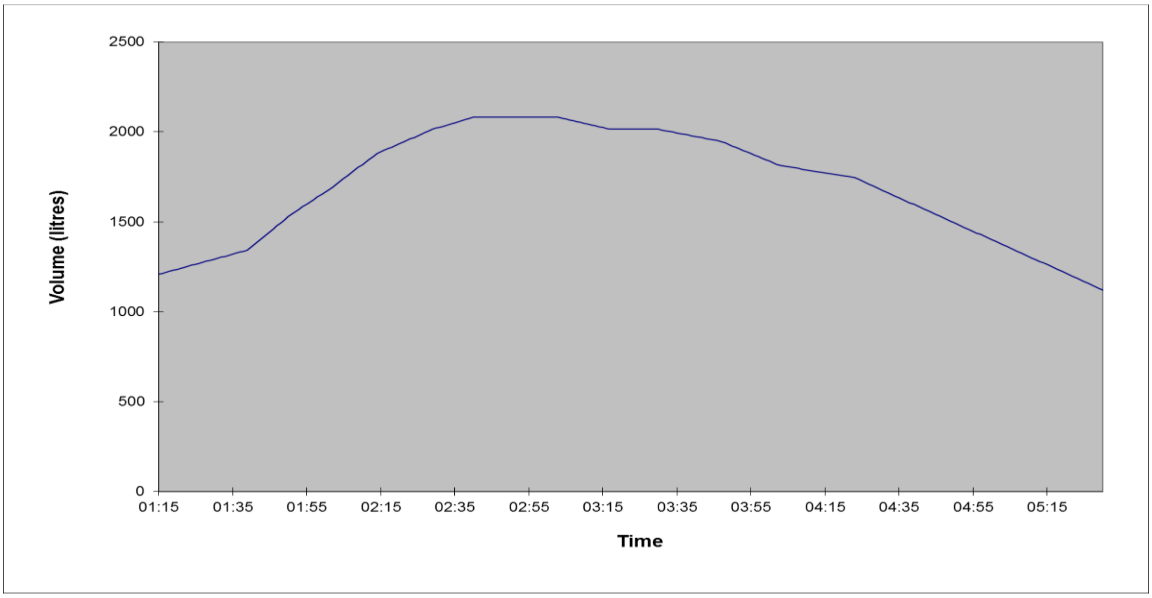


Figure 4.4a: Reaction of Terrace Khet HA1 to the July 11th Storm Event

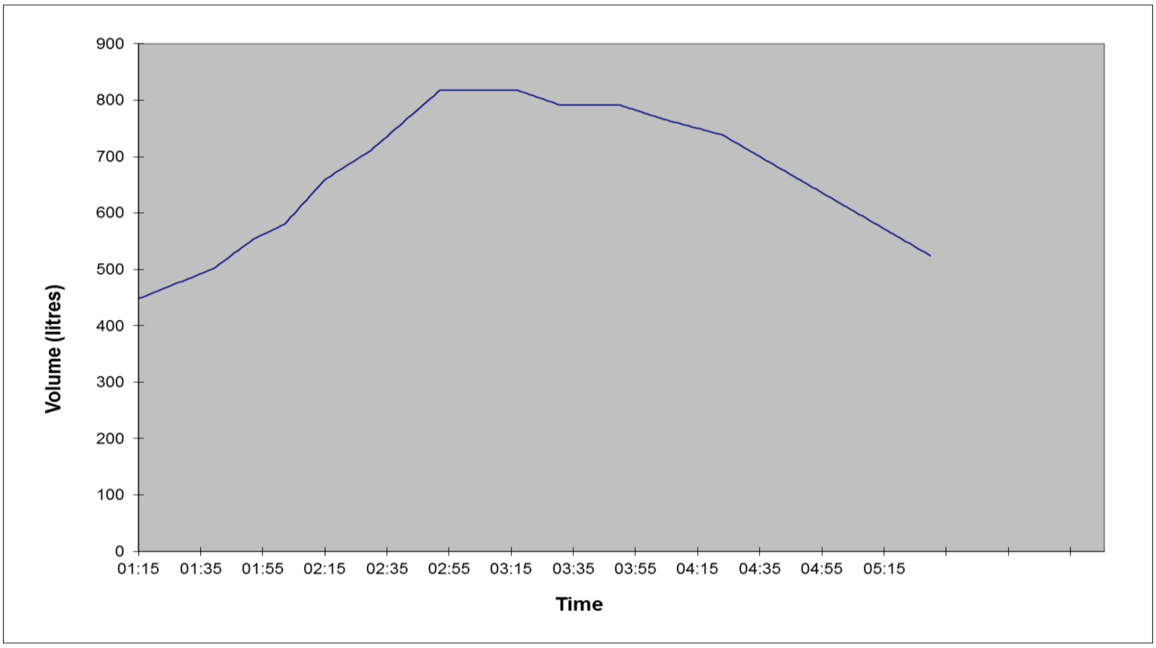
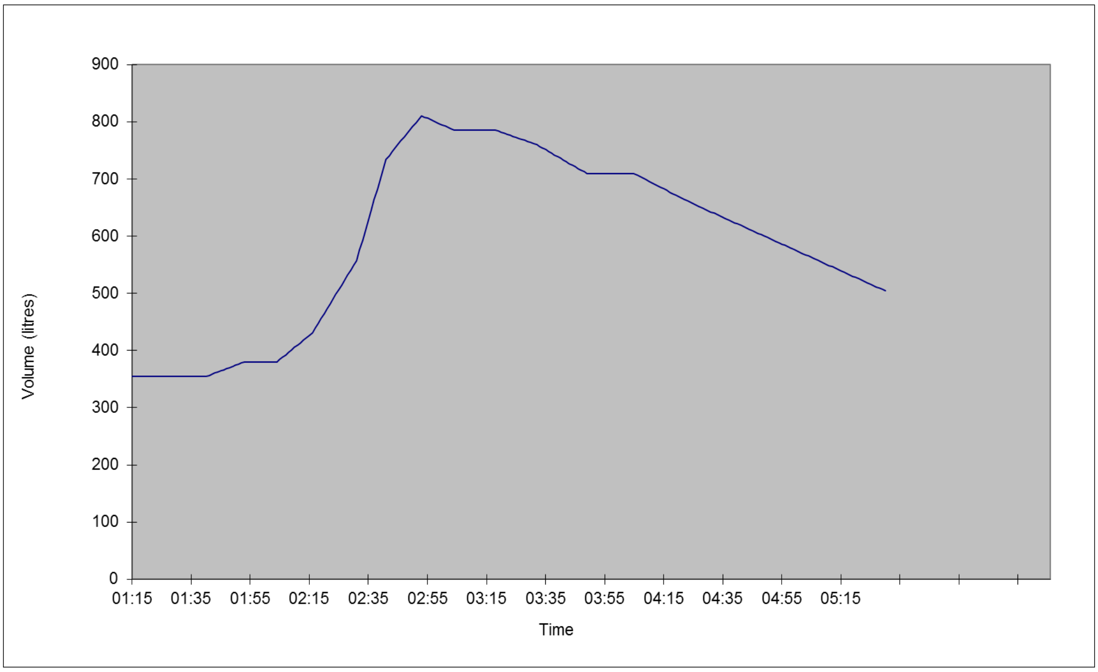


Figure 4.4b: Reaction of Terrace Khet HA2 to the July 11th Storm Event



Figures 4.4c: Reaction of Terrace Khet HA3 to the July 11th Storm Event

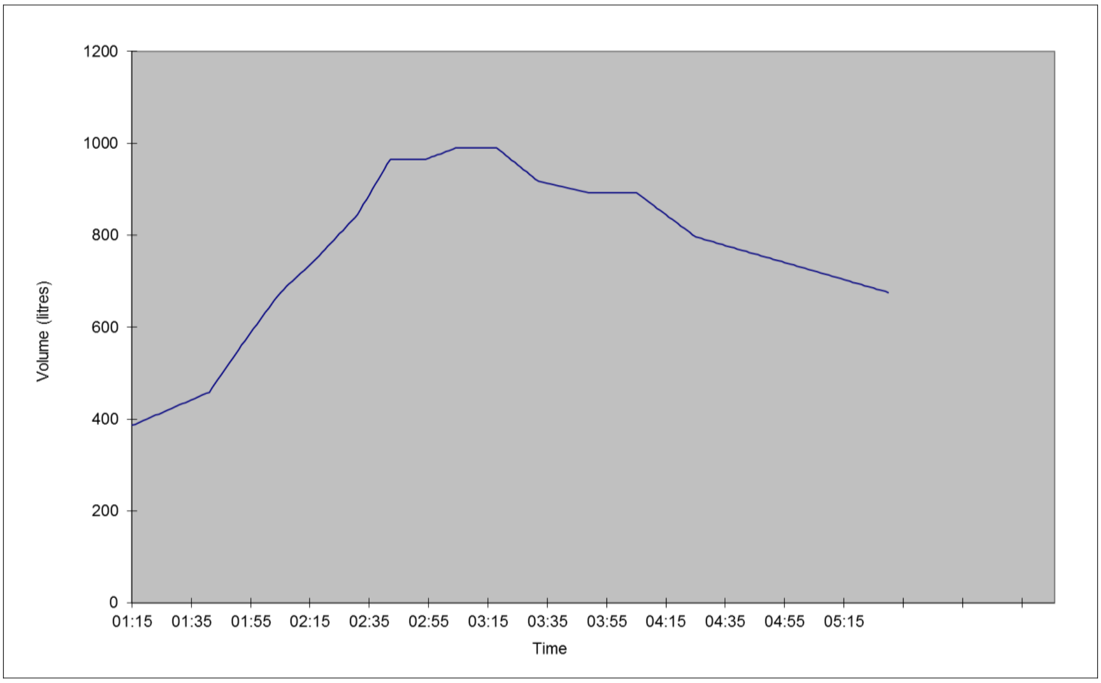


Figure 4.4d: Reaction of Terrace Khet HA to the July 11th Storm Event

4.8 Example of Model Application and the Method of Comparison of Field Data to the KhetFlow Model Prediction Data

The KhetFlow model was deployed for several hundred field simulations to complete the sensitivity analysis, calibration, validation and predictive applications during this research. For each of the calibration and validation applications the model prediction had to be compared to field data to test accuracy. This section explains how this was achieved, by stepping through the process for a representative application.

One of the calibration applications, model application July16-156 on terraces Khet HA, is used to illustrate the process. July16-156 refers to the modelling of a storm that occurred on July 16th using a fixed set of variables labelled 156. (The model variables were assigned values prior to each application and the set of variables given a numeric label used as a suffix.).

Khet HA is a series of 4 linear terraces, each roughly square with one inflow and one outflow, each central in the bund. The terrace areas were:

HA1 - 67.14 m^2
HA2 - 26.37 m^2
HA3 - 25.34 m^2
HA4 - 24.13 m^2

Table 4.7 – Characteristics of July 16th Storm Event

Event	Rainfall Duration mins	Rainfall Magnitude mm	Max Intensity mm/hour	Irrigation Start l/min	Peakflow l/min	End l/min	Model Duration mins
Jul-16	265	10	11.1	10	57	32	520

The July 16th event consisted of exactly 10mm of rain. Prior to the event irrigation was constant but of low volume at 10 l/min. Rainfall was mostly between midnight and 2.30am, inducing higher irrigation which peaked at 56 l/min before slowly declining to 32 l/min at the end of the monitoring period (see Table 4.7). Each terrace was monitored 21 times between 11pm and 4.30am and a final measurement was then taken at 7.40am the following morning. Table 4.8 records the field measurements.

Table 4.8 Field Measurements for July 16th Storm

	Irrigation		Terrace HA1		Terrace HA2		Terrace HA3		Terrace HA4	
No.	Time	Inflow Ht.	Time	OutFlow Ht.	Time	OutFlow Ht.	Time	OutFlow Ht.	Time	OutFlow Ht.
		(mm)		(mm)		(mm)		(mm)		(mm)
1	23.01	22	23.03	1	23.03	1	23.04	2	23.04	3
2	23.20	24	23.20	3	23.22	2	23.23	3	23.25	3
3	23.36	28	23.37	3	23.37	2	23.38	3	23.40	4
4	23.46	29	23.46	3	23.46	3	23.46	3	23.47	4
5	23.52	30	23.52	5	23.56	3	23.54	3	23.55	4
6	00.05	31	00.06	9	00.07	3	00.08	3	00.09	4
7	00.17	35	00.18	15	00.19	3	00.20	3	00.21	2
8	00.30	34	00.31	14	00.32	4	00.32	2	00.34	2
9	00.45	34	00.46	21	00.47	9	00.50	2	00.52	2
10	01.05	35	01.06	23	01.08	17	01.10	3	01.11	3
11	01.19	36	01.24	25	01.21	24	01.22	4	01.23	3
12	01.39	36	01.37	26	01.40	26	01.42	6	01.44	5
13	01.50	36	01.51	27	01.54	28	01.55	12	01.56	12
14	01.12	39	02.14	30	02.16	31	02.17	19	01.19	16
15	02.30	41	02.32	32	02.34	34	02.35	22	02.36	20
16	02.45	43	02.46	34	02.47	40	02.48	32	02.50	30
17	03.00	43	03.02	36	03.03	42	03.05	34	03.06	31
18	03.15	43	03.16	33	03.17	39	03.19	32	03.20	31
19	03.35	40	03.36	36	03.37	40	03.38	35	03.40	35
20	03.55	40	03.56	34	03.57	40	03.58	32	03.59	34
21	04.20	36	04.21	32	04.22	38	04.23	32	04.24	33
22	07.39	32	07.40	29	07.45	29	07.46	24	07.48	30

During each application of the model, change in volume in each terrace is calculated according to the continuity equation (Equation 2.1) on which the model is based, deployed in the manner illustrated by the model flow chart shown in Figure 2.4. Table 4.9 illustrates an extract from the results file then generated, showing the first twenty minutes of Application HA July16-156 for terrace 1 (start of rainfall at minute 14 can be clearly seen). For each terrace for each minute of the application the values shown in Table 4.9 are computed. These are explained in Table 4.10.

Table 4.9 Model Results Table for Application HA July16-156

Ter	Min	Vol	Change	Deps	Depe	r	e	k1	k2	qin1	qout1s	qout1e	fht1s	fht1e
1	1	742496	3956	11.00	11.61	0	336	9400	3693	10002	3	11	1.00	1.61
1	2	746577	4081	11.06	11.68	0	336	9400	3693	10135	11	13	1.61	1.68
1	3	750789	4212	11.12	11.74	0	336	9400	3693	10268	13	14	1.68	1.74
1	4	755133	4344	11.18	11.81	0	336	9400	3693	10401	14	15	1.74	1.81
1	5	759609	4476	11.25	11.88	0	336	9400	3693	10534	15	17	1.81	1.88
1	6	764216	4607	11.31	11.95	0	336	9400	3693	10667	17	19	1.88	1.95
1	7	768954	4738	11.38	12.03	0	336	9400	3693	10800	19	21	1.95	2.03
1	8	773823	4869	11.45	12.10	0	336	9400	3693	10933	21	23	2.03	2.10
1	9	778823	5000	11.53	12.18	0	336	9400	3693	11066	23	25	2.10	2.18
1	10	783954	5131	11.60	12.26	0	336	9400	3693	11199	25	27	2.18	2.26
1	11	789217	5263	11.68	12.34	0	336	9400	3693	11333	27	30	2.26	2.34
1	12	794610	5393	11.75	12.43	0	336	9400	3693	11466	30	33	2.34	2.43
1	13	800134	5524	11.84	12.51	0	336	9400	3693	11600	33	36	2.43	2.51
1	14	806519	6385	11.92	12.61	731	336	9400	3693	11733	36	40	2.51	2.61
1	15	813034	6515	12.01	12.72	731	336	9400	3693	11867	40	44	2.61	2.72
1	16	819678	6644	12.11	12.82	731	336	9400	3693	12000	44	49	2.72	2.82
1	17	826451	6773	12.21	12.92	731	336	9400	3693	12134	49	53	2.82	2.92
1	18	833353	6902	12.31	13.03	731	336	9400	3693	12267	53	59	2.92	3.03
1	19	840383	7030	12.41	13.14	731	336	9400	3693	12401	59	64	3.03	3.14
1	20	847541	7158	12.52	13.25	731	336	9400	3693	12534	64	70	3.14	3.25

Applying the continuity equation (Equation 2.1) to the values extracted from Table 4.9 for the first minute:

$$\frac{dSt}{dt} = \frac{(Qin + R + K2) - (E + K1 + Qout)}{dt}$$

Change in terrace 1 in minute 1 is:

3956 = (10002 + 0 + 3693) – (336 + 9400 + 3)

The volume of the terrace at the start of the application (minute 0) was 738540 ml (minute 0 is not shown in Table 4.9). At the end of minute 1 the value for change (3956 ml) is added to give a new volume of 742496 ml for terrace 1. This figure is then used to re-calculate depth and thus the flow height over the outflow weir which, using the transfer equation (Equation 2.2) is used to calculate the inflow in ml to terrace 2 for the next minute. The continuity of the model for each terrace is thus maintained by the model and values generated for the results tables shown below (Tables 4.11, 4.12 and 4.13).

Table 4.10 Computed Values for Minute 1, Terrace 1, for Application HA July16-156

Variable	Explanation	Value	Computation
Ter	Terrace Number	1	
Min	Minute	1	
Vol	Terrace volume (ml) at end of minute 1	742496	Volume at start of minute 1 (738540 ml) +/- change during minute 1
Change	Change in terrace volume (ml) during minute 1	3956	Used to calculate the value for water volume given above
Deps	Terrace depth (mm) at start of minute 1	11.00	Calculated terrace volume divided by area. Rounded only for printing purposes.
Depe	Terrace depth (mm) at end of minute 1	11.61	Calculated terrace volume divided by area. Rounded only for printing purposes.
r	Rainfall (ml) during minute 1	0	Rainfall (mm) x terrace area (m^2)
e	Evapotranspiration (ml) during minute 1	336	Evapotranspiration (mm) x terrace area (m^2)
k1	Seepage (ml) during minute 1	9400	Seepage (mm) x terrace area (m^2)
k2	Return flow (ml) during minute 1	3693	Return flow (mm) x terrace area (m^2)
Qin1	Inflow (ml) during minute 1	10002	Terrace 1 – Irrigation inflow: Other terraces – calculated outflow from terrace above
Qout1s	Outflow (ml/min) at the start of minute 1	3	Flow height (mm) x weir formula
Qout1e	Outflow (ml/min) at the end of minute 1	11	Flow height (mm) x weir formula
Fht1s	Flow height through outflow weir (mm) at the start of minute 1	1.00	Calculated volume divided by area, subtract weir clearance (10mm).
Fht1e	Flow height through outflow weir (mm) at the end of minute 1	1.61	Calculated volume divided by area, subtract weir clearance (10mm).

After the model has been activated and the application completed the raw output from the application feeds into an Excel spreadsheet previously populated with the field values for the event given in Table 4.8, the figures for each minute between the recorded field values being calculated by interpolation. The spreadsheet displays the model results alongside the field values, calculates least squares scores for the application and produces hydrographs to compare the model prediction with field values.

Table 4.11 Example of Comparison of Field and Model Values for Flow Height over the Outflow Weir, Application KHET HA - July 16-156

KHET HA - July 16-156

	Flow Height (mm)				Flow Height (mm)			
	HA1		HA2		HA3		HA4	
Minutes	Field	Model	Field	Model	Field	Model	Field	Model
1.00	1.00	1.00	1.00	1.00	2.00	2.00	3.00	3.00
2.00	1.00	1.06	1.00	0.91	2.00	1.91	3.00	2.91
3.00	1.00	1.12	1.00	0.82	2.00	1.82	3.00	2.82
4.00	1.12	1.18	1.05	0.73	2.00	1.73	3.00	2.72
5.00	1.24	1.25	1.11	0.64	2.05	1.64	3.00	2.63
6.00	1.35	1.31	1.16	0.55	2.11	1.55	3.00	2.54
7.00	1.47	1.38	1.21	0.46	2.16	1.45	3.00	2.45
8.00	1.59	1.45	1.26	0.37	2.21	1.36	3.00	2.36
9.00	1.71	1.53	1.32	0.28	2.26	1.27	3.00	2.27
10.00	1.82	1.60	1.37	0.19	2.32	1.18	3.00	2.17
↓			↓		↓			↓
512.00	29.12	31.46	29.36	30.45	24.32	29.44	30.12	28.43
513.00	29.11	31.46	29.32	30.45	24.28	29.44	30.11	28.42
514.00	29.09	31.46	29.27	30.45	24.24	29.44	30.09	28.42
515.00	29.08	31.46	29.23	30.45	24.20	29.44	30.08	28.42
516.00	29.06	31.46	29.18	30.45	24.16	29.44	30.06	28.42
517.00	29.05	31.46	29.14	30.45	24.12	29.44	30.05	28.42
518.00	29.03	31.46	29.09	30.45	24.08	29.44	30.03	28.42
519.00	29.02	31.46	29.05	30.45	24.04	29.44	30.02	28.42
520.00	29.00	31.46	29.00	30.45	24.00	29.44	30.00	28.42

Comparison is undertaken of both flow height and water volume because the former provides data for the least squares formula and the latter is more appropriate for producing terrace hydrographs. If least squares were calculated using terrace volume the accuracy of the model in predicting the behaviour of the larger terraces would have disproportionate influence. Comparison of flow heights discounts area from the calculation and thus has greater validity because each terrace prediction has equal weight.

Table 4.12 Example of Comparison of Field and Model Values for Terrace Water Volume, Application KHET HA - July 16-156

KHET HA - July 16-156

	Volume (l)		Volume (l)		Volume (l)		Volume (l)	
	HA1		HA2		HA3		HA4	
Time	Field	Model	Field	Model	Field	Model	Field	Model
23:01	739	742	290	288	304	302	314	311
23:02	739	747	290	285	304	299	314	309
23:03	739	751	290	283	304	297	314	307
23:04	746	755	291	281	304	295	314	305
23:05	754	760	293	278	305	293	314	303
23:06	762	764	294	276	307	290	314	300
23:07	770	769	296	274	308	288	314	298
23:08	778	774	297	271	309	286	314	296
23:09	786	779	298	269	311	283	314	294
23:10	794	784	300	266	312	281	314	292
↓		↓			↓			↓
07:32	2627	2783	1038	1067	870	999	968	927
07:33	2626	2783	1037	1067	869	999	968	927
07:34	2625	2783	1036	1067	868	999	967	927
07:35	2624	2783	1034	1067	867	999	967	927
07:36	2623	2783	1033	1067	866	999	967	927
07:37	2621	2783	1032	1067	865	999	966	927
07:38	2620	2783	1031	1067	864	999	966	927
07:39	2619	2783	1030	1067	863	999	966	927
07:40	2618	2783	1028	1067	862	999	965	927

Table 4.11 shows the comparison of field and model values for flow height over the outflow weir for each minute of the application; Table 4.12 shows the comparison of field and model values for terrace water volume; Table 4.13 shows an example of the least squares calculation for the data in Table 4.11; Figure 4.5 is an example of the hydrographs produced comparing model and field vales of terrace water volume, in this case using the data in Table 4.12.

Table 4.13 Example of Least Squares Scores, Application KHET HA - July 16-156

KHET HA - July 16-156

Summary and Totals

	HA1	HA2	HA3	HA4	Total 4 terraces
Total score	4411	5064	15986	11667	37127
Ave. per min.	8	10	31	22	71

Least Squares (of flow height so that terrace size is discounted)

Minute	HA1	HA2	HA3	HA4
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	1	0	0
8	0	1	1	0
9	0	1	1	1
10	0	1	1	1
↓	↓		↓	↓
512	5	1	26	3
513	6	1	27	3
514	6	1	27	3
515	6	2	27	3
516	6	2	28	3
517	6	2	28	3
518	6	2	29	3
519	6	2	29	3
520	6	2	30	2

In the summary at the top of Table 4.13 the total score is the sum of all rows for that terrace. This figure is then divided by the number of minutes (“Ave. per Minute”), partly to make the numbers more comprehensible but also to try to compare storms in different terrace systems, reported in Chapter 7. The least squares figure used for the purpose of comparison reported in Chapters 6 and 7 is the figure highlighted, the Total "Ave per Minute" for the four terrace. For this application the figure is 71.

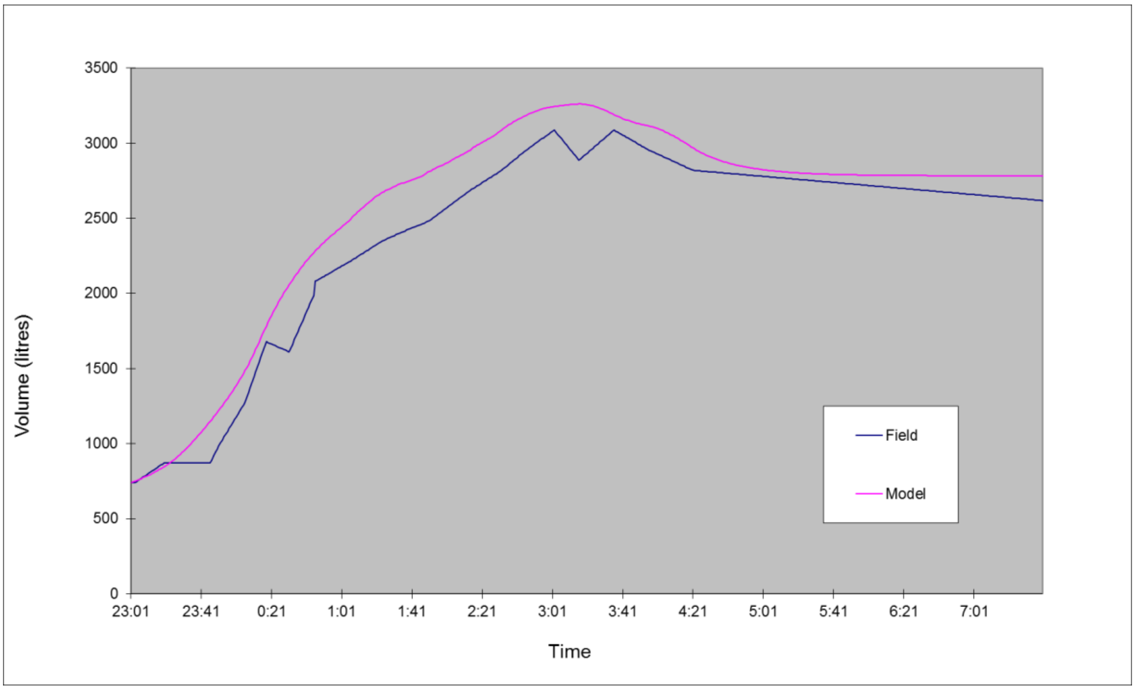


Figure 4.5 Example of a Hydrograph for Terrace Water Volume Generated by the Model

Throughout this thesis least squares figures are reported in a dimensionless manner. As explained above, the least square calculation represents the square of the difference between two flow heights (mm^2). However, the least squares for the whole model prediction are then totalled and a mean figure derived. The least squares score for the prediction is the total of the means from each terrace, designated as the "Whole System Value", to allow like for like comparisons during calibration and validation. As is explained in Section 7.5, to obtain like for like comparisons of subsystems with different numbers of terraces during validation, the "Whole System Value" was then divided by the number of terraces to give a "Terrace Mean System Value". It was considered that assigning units to such figures would be sufficiently tortuous as to hinder rather than aid understand and so least squares values are reported without dimensions.

4.9 Mass Balance Check

An important consideration in the model applications is that all the water is “accounted for”, that the total of all the water inputs to the system is balanced with the total of all the water output from the system, net of any change in storage. If some of the water is “missing” then there must be an error in the model and it cannot be said to be representing the intrinsic processes correctly.

Mass balance was checked by selecting one of the applications of the model and calculating the total of water inputs (rainfall, terrace inflow and return flow) for each terrace for each iteration (minute) of the application; calculating the total of water outputs (evapotranspiration, seepage and terrace outflow) for each terrace for each iteration of the application; and calculating the sum of the change in storage for each terrace for each iteration of the application. For the mass balance of water to be correct the difference between the total inputs and the total outputs should equal the total change in storage, which it did. The application used was from the storm on July 31 on Khet HA, July31-124. The model was deployed and the results produced in the manner described in Section 4.8, above and Table 4.14 provides a summary of these.

Table 4.14 Summary of Mass Balance Check from Table 4.3 (on DVD)

Total Inputs (Rain + Inflow + Return Flow)	58,443,992
Total Outputs (Seepage + Evapotranspiration + Outflow)	59,259,649
Total Inputs minus Total Outputs	815,657
Total Change in Storage	815,657
Net	0

This mass balance check only includes processes that have been measured in the field and included in the KhetFlow model. It does not include lateral surface flow out of the terrace subsystems, lateral subsurface flow, return flow input from higher on the hillslope and loss to ‘deep’ seepage. For the purpose of the modelling undertaken here these are assumed to be neutral but, as has been justified in Section 2.5, if they are not neutral they will be sufficiently low magnitude to not be important at the scale this research is being conducted.

Chapter 5 - Sensitivity Analysis

5.1 Introduction

The purpose of this chapter is to determine the relative importance of different variables within the model by systematically examining each terrace process and characteristic in order to suggest how much influence each has on the system. It starts by testing variables in the simplest situation of a single terrace and then progresses to consider variables in more complex and realistic situations on multi-terrace systems. Once the complications of multi-terrace systems are introduced the need to maintain a water balance in the system becomes apparent and the control this exerts on both the construction of khet systems in the real world and thus the modelling of these systems becomes evident. This is discussed in the chapter conclusion, where the implications for the rest of this research are considered, and is examined in detail in Chapter 8.

5.2 Sensitivity Testing Method and Sensitivity Criteria

The basis of the sensitivity testing is the modelling of a standard terrace system and environment in which each of the variables representing processes and terrace characteristics are amended in isolation to see which causes the greatest change to the system during rainfall. To that end, the KhetFlow Model is used to define a uniform khetland system with appropriate processes, initially set at constant rates typical of field values in Nepal (as estimated during the pilot study). The model was then utilised to run a series of tests (Model Applications) whereby a monsoon storm of representative intensity was imposed on the system under varied but controlled conditions. The impact of each variation on the system as a whole was calculated and compared.

The sensitivity analysis exercise was primarily undertaken on the khet system at its simplest level of one terrace. Initial applications of the model were performed on this single terrace to explain which variables were most influential in this most basic unit of the system. This does not negate the conclusions drawn at the end of the pilot study;

that the difficulty in explaining the behaviour of the whole system lay as much in understanding the interaction between the terraces as it did in understanding the behaviour of individual terraces. It is the purpose of the model to replicate the full khet system and water flow through a full khet system is more complex than through a single terrace. However, from the point of view of analysis of sensitivity it is reasonable to speculate that the most sensitive variables through the complete system will be replications of the most sensitive variables on one terrace. The complexity of a full system is the cumulative impact down the system of any one variable in any one terrace. It is thus valid to initially perform the sensitivity exercise on one terrace and then undertake further analysis on longer terrace systems to examine the complexities then introduced. Consequently, sensitivity analysis was also undertaken on khet systems comprising of four and twenty five terraces, the latter being particularly important because it is more representative of the sub-systems into which hillslopes are divided in the Middle Hills.

It is the aim of the Khetland Flow Model to predict the surface hydrology of khet systems during monsoon storms but it is also desirable to achieve this from as few measured variables as possible; if fewer variables are required then less fieldwork is needed to apply the model, an important consideration in Nepal because of the difficulty collecting field data there. The pilot study indicated that rates of rainfall and irrigation inflow were of much greater magnitude than evapotranspiration, seepage and return flow. This chapter reaches the same conclusion from a modelling perspective, which also provides greater confidence in the decisions taken about the scale and accuracy required in the measurement of the lower impact field processes.

If Chapters 6 and 7 show that the model predictions are accurate within acceptable limits by calibration and validation against the main body of fieldwork, it is reasonable to suggest that the internal logic of the model is correct and that field work is being conducted at the appropriate scale. This chapter adds weight to the idea that surface khet hydrology can be predicted from a few measured variables, specifically those related to rainfall and the volume and mechanics of flow, whilst region averages can be attributed to less important processes such as evapotranspiration, seepage and return flow.

The processes and terrace characteristics that affect flow through each terrace are:

- Rainfall intensity;
- Rainfall duration;
- Irrigation input rate;
- Evapotranspiration;
- Seepage;
- Return flow;
- Outflow rate, determined as a combination of water depth, outlet width and outlet clearance;
- Terrace area;
- Flow constraints, including:
    - crop stage;
    - clod height (at low depths);
    - flowline (between inlet and outlet).

The rationale of the sensitivity exercise was to model the behaviour of fictional khet terraces of dimensions typical of terraces in the hills of Nepal in response to rainfall, using process rates representative of khet systems (as measured during the pilot study). The “Standard Storm” was repeatedly modelled on the fictional terraces, varying individual dimensions or process rates during each application, so that the magnitude of the effect of each could be isolated.

Terraces in the field obviously vary in shape and size (see Section 2.5) and such variation is likely to influence the behaviour of the khet system. However, for the purpose of this sensitivity analysis exercise terrace dimensions were kept uniform so that changes in other variables could be isolated (except when changes to characteristics of the terrace are specifically being tested). Terrace dimensions and default process rates used during the sensitivity analysis are shown in Table 5.1.

Because of the dynamic interaction between variables in the system several criteria have to be used to evaluate change. The continuity equation dictates that if process rates are held constant each terrace system will revert to a stable position in which inputs and outputs balance (except in the situations where the system is overrun and overflows or dries out).

Table 5.1 Terrace Dimensions, Default Process Rates and Equilibrium Position used for the Sensitivity Analysis

Terrace Dimensions	
Area	100 m^2
Bund height	150 mm
Capacity	15,000 l
Outlet clearance from terrace floor	25 mm
Outlet width	200 mm
Default Process Rates	
Irrigation inflow	10 l/min
Evapotranspiration	5 ml/m^2/min
Seepage	5 ml/m^2/min
Return flow	0 ml/m^2/min
Equilibrium Position at these Rates (explained below)	
Volume	2,950.285 l
Water Depth	29.50 mm
Outflow	9 l/min
Flow height over outflow weir	4.50 mm

This stable position is the equilibrium position referred to in Table 5.1 and is an important consideration in the sensitivity analysis. For the following tests to be valid the equilibrium position for the terrace must be determined before rainfall is applied. However, the system represented is a dynamic environment and the equilibrium position will change in response to change in any variable. Thus, even before rainfall starts, the equilibrium position of the system will shift when the variable to be tested is changed and subsequent monitoring of system reaction becomes more complex.

This is illustrated by considering changes to the default rates listed in Table 5.1. When these process rates are applied to a single terrace system the system will settle to the equilibrium position at the volume of water and outflow rate given in the table (in any one minute the change of water volume in the terrace will be a balance of gains from irrigation water and losses to evapotranspiration, seepage and water exiting through the terrace outflows).

In the application illustrated in Table 5.1 the inflow of irrigation water is 10 l/min and the system has found an equilibrium position reflecting this and other process rates. If inflow of irrigation water is increased to 20 l/min whilst all other process rates remain constant (as in the sensitivity test described in Model Application T1-IR20-Eq) then the equilibrium position of the terrace will be one of greater volume, depth and outflow than when irrigation was at the lower level. The sensitivity analysis is based on the monitoring of the fictionalised khet system during a storm but before each application it is important to wait until the system “settles down” to a new equilibrium position before rainfall is introduced to be sure that when measuring reaction to rainfall it is not the system moving towards its new equilibrium position that is being measured.

Because of this and for other reasons explained below, there is no one absolute criterion by which to measure the sensitivity of individual variables. Several methods are used to measure the magnitude of change when variables are tested but these have to be interpreted to explain relative sensitivity.

The criteria used are:

1. Maximum increase, in absolute terms, in the volume of water in the terrace over that of the pertaining equilibrium position;
2. Time taken for the system to return to the pre-storm equilibrium position after rainfall has ceased;
3. Sum of squares differences between the hydrograph of the application and that of the “Benchmark Test”. Calculating sum of squares was explained in Chapter 4 and is further discussed in Chapter 6.

The criterion of the ratio of percentage change in output to percentage change in input was also considered but rejected as in the system being modelled it was not possible to create like for like comparisons using such a method because of the dynamic nature of the equilibrium start position.

Other figures, for example, peak volume and peak outflow, might help to explain different responses but are invalid for purposes of comparison also because of the different equilibrium start positions. Similarly, percentage increase in water does not provide a valid comparison for the same reason and also because absolute depth is an arbitrary figure, as is seen in Model Application T1-Clear55, determined mainly by the height of the bottom of the terrace outlet over the terrace floor.

When the equilibrium position has been established for each test, rainfall is introduced to the system at a constant rate for a fixed period of time and the extent of change measured. A storm of constant intensity of 60 mm/hr is applied for the duration of 1 hour (except when it is variation in rainfall that is being tested). This is referred to as the ‘Standard Storm’ and the ‘Standard Test’ is the application of the Standard Storm to the system when it is in equilibrium. The “Benchmark Test” for the single, 4 and 25 terrace systems is the Standard Storm applied to those systems at the default rates given in Table 5.1.

If a storm of the magnitude utilised for this analysis occurred in the field, the intensity and total rainfall recorded would represent a reasonably heavy but not unusual monsoon storm in Nepal, as recorded by HMG Nepal (1997), who report storm magnitudes for over one hundred sites in Nepal for up to 20 years. Intensity would, of course, normally vary throughout the storm. Mawdesley and Gardner (1998) provide detailed rainfall records for three monsoon seasons in four to eight sites in Nepal, reporting five to fifteen minute high intensity bursts interspersed with steadier lighter rain as a more typical pattern. However, for the purposes of these sensitivity tests rainfall intensity is kept constant so that changes caused by the variable being tested are not confused with those caused by intensity variations.

The model was deployed for each application of the sensitivity analysis in the manner described in Section 2.6 and the results synthesised as explained in Section 4.8. The variable settings for all the model applications testing the sensitivity of a single terrace system and the test references are summarised in Table 5.2. The results format was also explained in Section 4.8. Each application generated one of the tables there described, usually of several thousand rows, each containing 14 variables. Such datasets are unmanageable in their raw form and the results need rationalisation. For the purpose of the analysis reported in this chapter this is provided by the graphs and tables shown below, where the data for each application are summarised.

Table 5.2 Summary of Sensitivity Analysis Model Applications

				Initial Position								Weir			Storm			
Model	Test Reference	Application	Area	Volume	Depth	Outflow	Flow ht	Qin1	Evap.	Seep.	R. Flow	Width	Height	Clearance	Duration	Intensity	Rain	Start/End
Ref.			(m2)	(ml)	(mm)	(ml/min)	(mm)	(ml/min)	(all units ml/min/m^2)			(mm)	(mm)	(mm)	(mins)	(mm/hr)	(mm)	(mins)
T1-1	T1-Eq	Establish System Equilibrium	100	2950000	30	9000	5	10	5	5	0	200	125	25	0			
T1-2	T1-Benchmark	Standard Storm - Benchmark Test	100	2950000	30	9000	5	10	5	5	0	200	125	25	60	60	60	30/90
T1-3	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	100	2950000	30	9000	5	10	5	5	0	200	125	25	60	30	30	30/90
T1-3a	T1-Rain30d120	As T1-3 but duration 120 mins	100	2950000	30	9000	5	10	5	5	0	200	125	25	120	30	60	30/150
T1-4	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	100	2950000	30	9000	5	10	5	5	0	200	125	25	60	90	90	30/90
T1-5	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	100	2950000	30	9000	5	10	5	5	0	200	125	25	60	120	120	30/90
T1-6	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	100	2950000	30	9000	5	10	5	5	0	200	125	25	60	150	150	30/90
T1-9	T1-IR0	Canal inflow closed, Qin zero - Standard storm	100	2500000	25	0	0	5	5	5	0	200	125	25	60	60	60	30/90
T1-10	T1-IR20-Eq	Increase Qin to 20ml/min - est. equilibrium position	100	3350000	34	19000	9	20	5	5	0	200	125	25				
T1-11	T1-IR20	Increase Qin to 20ml/min - Standard storm	100	3350000	34	19000	9	20	5	5	0	200	125	25	60	60	60	30/90
T1-12	T1-IR15-Eq	Increase Qin to 15ml/min - est. equilibrium position	100	3150000	32	14000	7	15	5	5	0	200	125	25				
T1-13	T1-IR15	Increase Qin to 15ml/min - Standard storm	100	3150000	32	14000	7	15	5	5	0	200	125	25	60	60	60	30/90
T1-14	T1-IR25-Eq	Increase Qin to 25ml/min - est. equilibrium position	100	3550000	36	24000	11	25	5	5	0	200	125	25				
T1-15	T1-IR25	Increase Qin to 25ml/min - Standard storm	100	3550000	36	24000	11	25	5	5	0	200	125	25	60	60	60	30/90
T1-16	T1-IR30-Eq	Increase Qin to 30ml/min - est. equilibrium position	100	3750000	38	29000	13	30	5	5	0	200	125	25				
T1-16a	T1-IR100-Eq	Increase Qin to 100ml/min - est. equilibrium position	100	5850000	59	99000	34	100	5	5	0	200	125	25				
T1-17	T1-IR30	Increase Qin to 30ml/min - Standard storm	100	3750000	38	29000	13	30	5	5	0	200	125	25	60	60	60	30/90
T1-17a	T1-IR100	Increase Qin to 100ml/min - Standard storm	100	5850000	59	99000	34	100	5	5	0	200	125	25	60	60	60	30/90
T1-18	T1-IR8-Eq	Reduce Qin to 8ml/min - est. equilibrium position	100	2850000	29	7000	4	8	5	5	0	200	125	25				
T1-19	T1-IR8	Reduce Qin to 8ml/min - Standard storm	100	2850000	29	7000	4	8	5	5	0	200	125	25	60	60	60	30/90
T1-20	T1-IR6	Reduce Qin to 6ml/min - Standard storm	100	2750000	28	5000	3	6	5	5	0	200	125	25	60	60	60	30/90
T1-20a	T1-IR6-Eq	Est. system equilibrium for T1-20	100	2750000	28	5000	3	6	5	5	0	200	125	25				
T1-21	T1-IR4	Reduce Qin to 4ml/min - Standard storm	100	2650000	26	3000	2	4	5	5	0	200	125	25	60	60	60	30/90
T1-22	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	100	3050000	30	10000	5	10	0	0	0	200	125	25	60	60	60	30/90
T1-22a	T1-ESR0-Eq	Est. system equilibrium for T1-22	100	3050000	30	10000	5	10	0	0	0	200	125	25				
T1-24	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	100	2850000	29	7500	4	10	20	5	0	200	125	25	60	60	60	30/90
T1-24a	T1-Evap20-Eq	Establish system equilibrium for T1-24	100	2850000	29	7500	4	10	20	5	0	200	125	25				
T1-25	T1-Seep333	Evap = 5, Seepage = 333, Ret.flow = 0	100	3000000	30	10000	5	10	5	333	0	200	125	25	60	60	60	30/90

Table 5.2 Summary of Sensitivity Analysis Applications (cont)

				Initial Position								Weir			Storm			
Model	Test Reference	Application	Area	Volume	Depth	Outflow	Flow ht	Qin1	Evap.	Seep.	R. Flow	Width	Height	Clearance	Duration	Intensity	Rain	Start/End
Ref.			(m2)	(ml)	(mm)	(ml/min)	(mm)	(ml/min)	(all units ml/min/m^2)			(mm)	(mm)	(mm)	(mins)	(mm/hr)	(mm)	(mins)
T1-26	T1-Area200-Eq	Increase Area to 200m2, est. system equilibrium	200	5900000	30	8000	4	10	5	5	0	200	125	25				
T1-27	T1-Area200	Area 200m2, Standard storm	200	5900000	30	8000	4	10	5	5	0	200	125	25	60	60	60	30/90
T1-28	T1-Area200R30	Area 200m2, storm intensity 30 mm/hr	200	5900000	30	9000	5	10	2	3	0	200	125	25	60	30	30	30/90
T1-29	T1-Area50	Area 50m2, Standard storm	50	1475000	30	9500	5	10	5	5	0	200	125	25	60	60	60	30/90
T1-29a	T1-Area50-Eq	Area 50m2, Standard storm, Est. equilibrium	50	1475000	30	9500	5	10	5	5	0	200	125	25				
T1-30	T1-Area50R120	Area 50m2, storm intensity 120 mm/hr	50	1475000	30	9000	5	10	10	10	0	200	125	25	60	120	120	30/90
T1-31	T1-Rinfinity	Continuous rain, new equilibrium achieved	100	2950000	30	9000	5	10	5	5	0	200	125	25	1470	60	1470	30/1500
T1-32	T1-Clear50	Change weir clearance, Standard Storm	100	5450000	55	9000	5	10	5	5	0	200	100	55	60	60	60	30/90
T1-32a	T1-Clear50-Eq	Change weir clearance, Est. equilibrium	100	5450000	55	9000	5	10	5	5	0	200	100	55				
T1-33	T1-Wide-Eq	Change weir width (inc. outflow), est. equilibrium	100	2750000	28	9000	3	10	5	5	0	O x2*	125	25				
T1-34	T1-Wide	Inc. Outflow, standard storm	100	2750000	28	9000	3	10	5	5	0	O x2*	125	25	60	60	60	30/90
T1-35	T1-Narrow-Eq	Change weir width (lower. outflow), est. equilibriun	100	3350000	34	9000	9	10	5	5	0	O /2*	125	25				
T1-36	T1-Narrow	Lower Outflow, standard storm	100	3350000	34	9000	9	10	5	5	0	O /2*	125	25	60	60	60	30/90
T1-37	T1-Vweir-Eq	V-shaped Weir, establish equilibrium	100	4600000	46	9000	21	10	5	5	0	V *	125	25				
T1-38	T1-Vweir	V-shaped Weir, standard storm	100	4600000	46	9000	21	10	5	5	0	V *	125	25	60	60	60	30/90
T1-46	T1-CP110	Set CP = 1.1, no rain	100	2695000	30/	9000	5	10	5	5	0	200	125	25	0	0	0	
T1-47	T1-CP125	Set CP = 1.25, no rain	100	2370000	30/	9000	5	10	5	5	0	200	125	25	0	0	0	
T1-48	T1-CP110	Set CP = 1.1, Standard storm	100	2695000	30/	9000	5	10	5	5	0	200	125	25	60	60	60	240/300
T1-49	T1-CP125	Set CP = 1.25, Standard Storm	100	2370000	30/	9000	5	10	5	5	0	200	125	25	60	60	60	240/300
Notes O*2 = Outflow Doubled O /2 = Outflow Halved V = V-shaped Weir																		

5.3 Correction to Model Error

A small error in the model at this stage in its development, coupled with the very fine sensitivity of the model, meant that each minute the calculated volume fluctuated marginally to either side of the true value when the system is in equilibrium. The error occurred because the model (not the physical system) is driven by the calculated height of flow across the outlet weirs. Flow rates are calculated from this figure and then used, together with the other, pre-set variables, to determine terrace volume and depth for the next iteration. Height of flow is calculated to the nearest millimetre, flow rates to millilitres per minute. The weir calibration graph (Figure 3.1) shows that when calculating flow rates a change of one millimetre in height makes a difference of over a litre, or 1000 millilitres, per minute.

In the example of Table 5.18, an extract from the results of KhetFlow Application T1-Eq, stability is calculated by the model at a volume of 2,950,285 millilitres, a depth of 29.50285 mm and, because there is 25mm clearance between the terrace floor and the base of the weir, flow height of 4.50285 mm across the outlet weir. In the uncorrected version the model rounds this to 5mm, which translates to a flow rate of 9.884 l/min out of the terrace across the weir, a slight over-exaggeration. The over-exaggeration results in the model slightly reducing the volume of water in the terrace in the next iteration, and thus depth and flow height are slightly reduced. This causes the model to round down flow height to 4mm, which translates to a reduced flow rate of 7.547 l/min, which sets the process into reverse and the flow height is rounded up to 5mm. Hence the reported value fluctuates marginally around the true value and the design structure of the model is introducing a small inaccuracy. This can be seen in Table 5.3 where the flow height fluctuates between 4mm and 5mm, producing a change in volume of 884ml and 1453ml respectively, when flow height should be constant at 4.50285 mm and change in volume should be 0. It also produces the slightly stepped nature of some of the hydrographs referred to below. In this application the input from irrigation is only 10,000 ml/min. As outputs must equal input and evapotranspiration and seepage have been set at 5 ml/min/m^2 (equiv. 500 ml/min each), outflow must be 9,000 ml/min.

Table 5.3 Results Extract Showing Rounding Error

Ter	Min	Vol	Change	Deps	Depe	qout1s	qout1e	fht1s	fht1e
1	1	2949116	-884	30	29	9884	7547	5	4
1	2	2950569	1453	29	30	7547	9884	4	5
1	3	2949685	-884	30	29	9884	7547	5	4
1	4	2951138	1453	29	30	7547	9884	4	5
1	5	2950254	-884	30	30	9884	9884	5	5
1	6	2949370	-884	30	29	9884	7547	5	4
1	7	2950823	1453	29	30	7547	9884	4	5
1	8	2949939	-884	30	29	9884	7547	5	4
1	9	2951392	1453	29	30	7547	9884	4	5
1	10	2950508	-884	30	30	9884	9884	5	5
1	11	2949624	-884	30	29	9884	7547	5	4
1	12	2951077	1453	29	30	7547	9884	4	5
1	13	2950193	-884	30	30	9884	9884	5	5
1	14	2949309	-884	30	29	9884	7547	5	4
1	15	2950762	1453	29	30	7547	9884	4	5

The application runs for nearly 5 hours (296 minutes) after which the mean values for outflow for each minute (which should net to 9000 ml/min) and change (which should net to zero as the system is in equilibrium) were 8999.73 and 0.27 ml/min respectively, a 0.27 ml net inaccuracy over the five hour period. In later applications of the model this small inaccuracy was eliminated by a design change (the programming error introduced by incorrect rounding was eliminated) but the inaccuracy, though clearly visible in some figures and diagrams, is too small to alter the conclusions drawn from this sensitivity analysis and did not warrant the work being repeated.

5.4 Sensitivity Analysis for a Single Terrace System.

5.4.1 The Benchmark Test: The Standard Storm Applied to the Single Terrace System

The single terrace used in these applications is of the dimensions given in Table 5.1 with one inlet and one outlet. The equilibrium position at the default rates is:

Volume	2,950 l
Water Depth	29.50 mm
Outflow	9 l/min
Flow height (over outflow weir)	4.50 mm

Peak volume, depth and outflow were attained at the point the storm ends, when terrace values were:

Peak Volume	5,770 l
Peak Depth	58 mm
Peak Outflow	96.67 l/min
Peak Outflow Height	33 mm

The maximum increase in volume was 2,821 litres
The system returned to pre-storm stability 131 minutes after the end of the storm.

These figures are used as the Benchmark Test for the single terrace system, against which all other applications on this system are compared. Figure 5.1a illustrates the individual components of volume change. The combination of these and thus the reaction of the terrace is illustrated in the hydrograph of volume, Figure 5.1b.

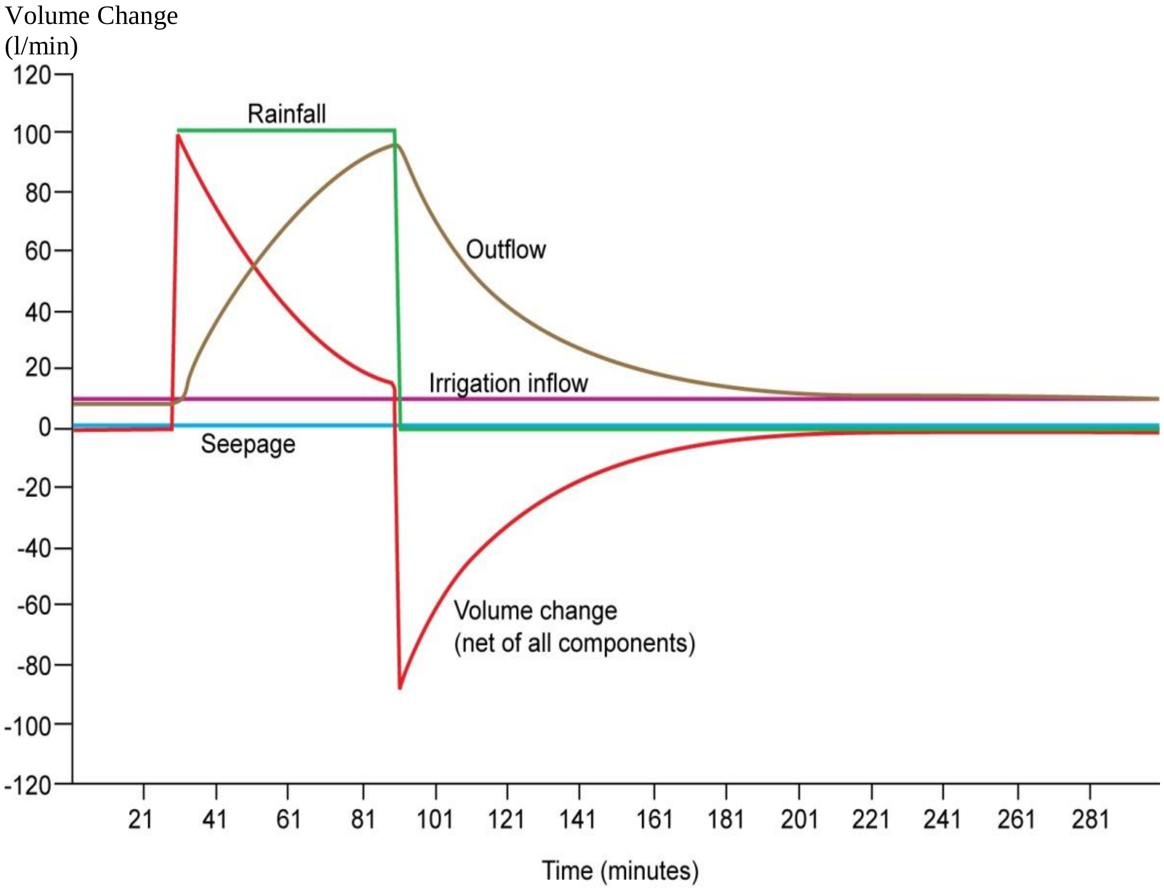


Figure 5.1a Components of Volume Change on the Single Terrace when the Standard Storm is Applied (Volume change in l/min of each component)

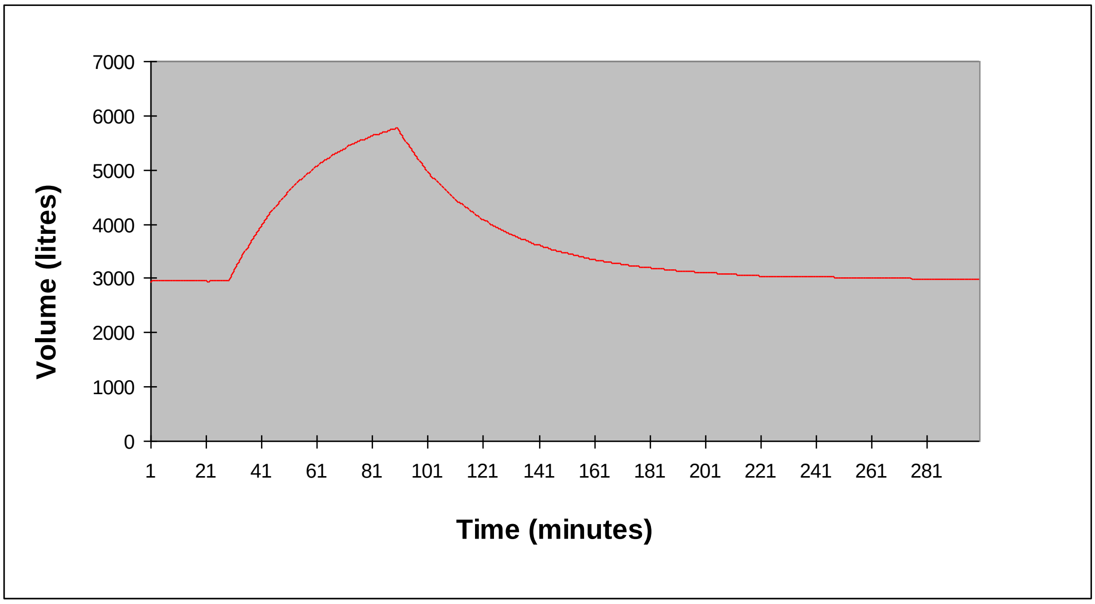


Figure 5.1b Change in Absolute Volume During Application of the Standard Storm

The unusual shape of the hydrograph in Figure 5.1b, pointed with regular curves, should be commented on. A more usual shape for a hydrograph, for instance for a natural system river, would exhibit much fluctuation, a lag between the end of a storm and peak flow and then a gradual decline into the falling limb. The reason this is not seen in the model hydrograph is partly due to the manner in which processes work in the khet system, and partly due to the artificial nature of the tests. Process rates are held constant or change abruptly so that they can be viewed in isolation; for example, rainfall is abruptly turned on and then intensity is held constant for this exercise. Instantaneously “turning on” constant rainfall causes the sharp initial rise in the rising limb and the distinct peak in the hydrograph.

A more subtle process causes the convex shape of the rising limb and concave shape of the falling limb depicted in Figure 5.1b. The curved shape is due to the non-linear change in flow rate over the outflow weir (Shaw, 1994). As outflow scales by a power based function with depth and is therefore greater per unit input of rainwater, so less water is retained in the terrace per unit input of rainwater. Because in this application rainfall input is constant, as the storm progresses the rate of volume increase declines and the hydrograph becomes convex. The reverse is true on the falling limb. Figure 5.2 shows that the hydrograph of terrace draining is now negative in a non-linear manner.

These non-linear responses can be seen in all the sensitivity tests reported here and are particularly relevant to the cumulative response to rainfall propagating down terrace systems.

Having established an equilibrium position for the single terrace system at the default rates and applied the Standard Storm to this to define the Benchmark Test, a series of applications were run to determine the relative magnitude of change brought about by variation in rainfall amount and intensity, irrigation inflow, evapotranspiration, seepage, return flow, terrace size, outflow rates, weir size and that of flow constraints across the terrace. Because of the nature of the system, it was sometimes difficult to perform like for like tests. Where this was the case the adjustments that had to be made and the reasons for this are explained.

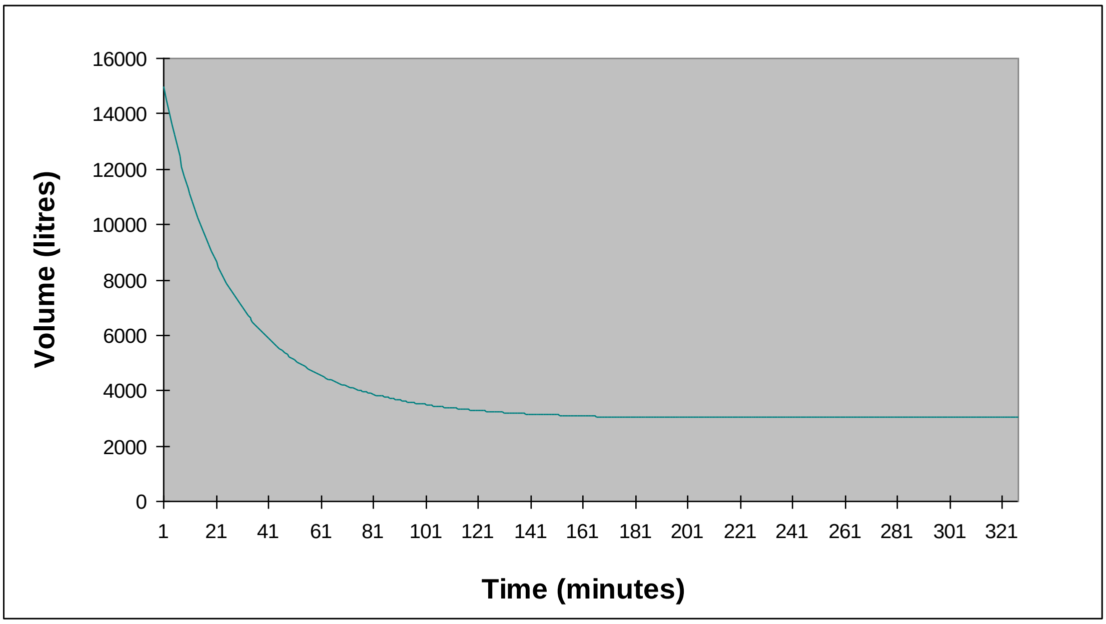


Figure 5.2 Terrace Draining from Full to the Equilibrium Position under the same conditions as the Standard Test

Table 5.2 details all the applications and the subsequent results of changing variables on a single terrace system. Tables 5.7a, b and c rank and summarise the sensitivity of all of the applications by the three criteria, Maximum Volume Increase, Time to

Stability and Least Squares. Each set of changes and their impact is now considered individually.

5.4.2 Response of the Single Terrace System to Changes in Rainfall Intensity

In Model Applications T1-Rain30, T1-Rain90, T1-Rain120 and T1-Rain150 the system characteristics and process rates are as above, but rainfall intensity is changed to 30, 90, 120 and 150 mm/hour respectively. This obviously also changes the magnitude of each storm. As would be expected, the reaction of the terrace is stronger with higher rainfall inputs and lessened when rainfall input was lower. Figure 5.3 shows the hydrograph of each application (for comparison purposes, shown as increase in volume rather than absolute volume) and Table 5.4a summarises numerically the change in volume and the time the systems takes to return to stability.

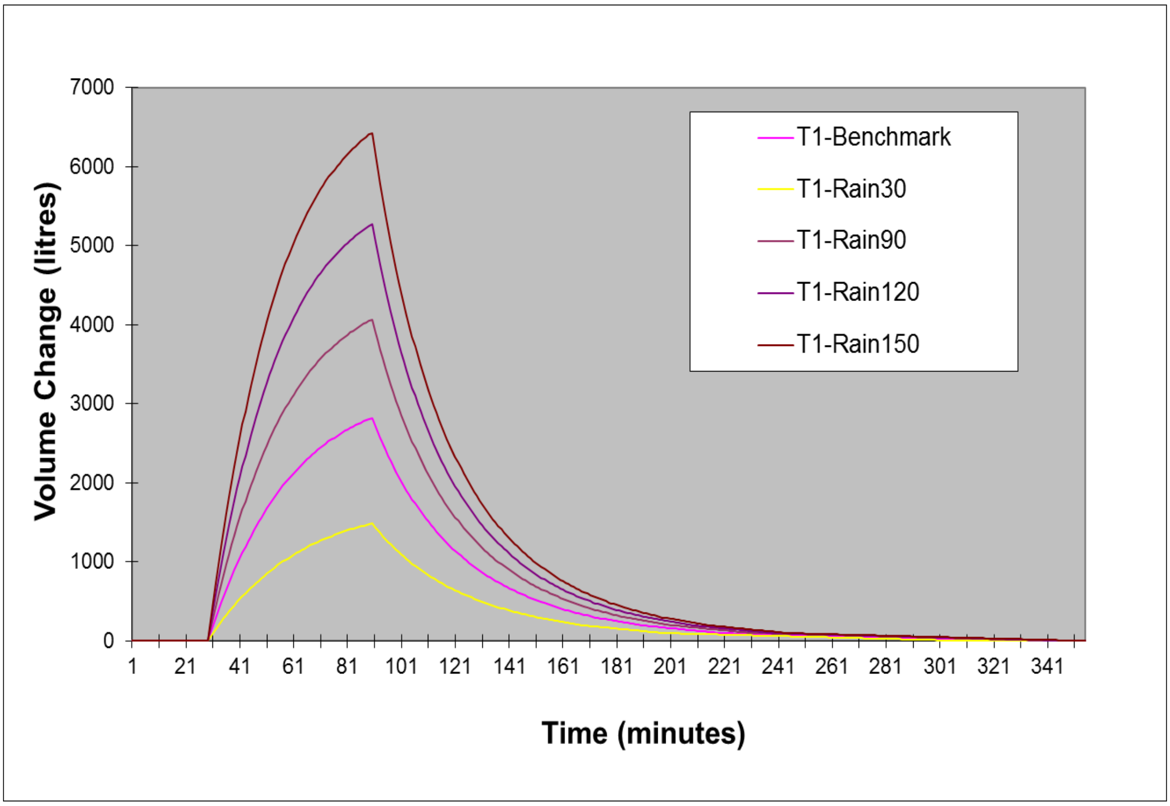


Figure 5.3 Comparison of Terrace Volume Change for Different Rainfall Intensities

Table 5.4a Summary of Terrace Reaction to Storms of Different Intensities

Ref.	Intensity (mm/hr)	Increase in: Volume (l)	Increase in: Depth (mm)	Increase in: Outflow (l)	Time to Stability (mins)
T1-Rain30	30	1485	14.8	40.6	109
T1-Benchmark (Benchmark Test)	**60**	**2821**	**28.2**	**87.7**	**131**
T1-Rain90	90	4067	40.6	130.7	143
T1-Rain120	120	5269	52.7	178.2	150
T1-Rain150	150	6427	64.3	226.8	156

Table 5.4a shows that volume, depth, outflow and stability times of the applications all increase with intensity and illustrates the non-linear rates of change induced by the nature of flow over the outflow weir (Shaw (1994), explained in Section 5.4.1 above). Across the series of results, drainage rates increase by a power function related to depth as volume increases but this slows down the increase in volume, depth and time to stability. This is because, as drainage rates scale by a power function as volume increases, the retention of water in the terrace, though also increasing in absolute terms when intensity increases, must reflect the increased loss of water.

For the same reason, during the falling limb of the hydrograph drainage rates are greatest per mm fall in water depth just after the storm has ended. As the terrace achieves greater volume when intensity is higher, initial drainage rates will be greater after storms of higher intensity. Therefore, whilst the time taken to return to stability will increase in line with higher intensity and greater depth/volume increase during the storm, simply because there is more water to drain, the increase will be non-linear. Model Application T1-Drain shows the terrace draining from full under the same conditions as the Benchmark Test and the non-linear shape of the curve is clearly seen in figure 5.2.

5.4.3 Response of the Single Terrace System to Changes in Rainfall Duration

To test rainfall duration only (as opposed to rainfall duration **and** storm magnitude) the sensitivity of the system was assessed by considering each of the applications tested in 5.4.2 above but then assessing the state of the system when the same total amount of rain (60mm) has fallen as in the Standard Storm. This meant that at intensities of 30, 60, 90, 120 and 150 mm/hour the duration of the storms were 120, 60, 40, 30 and 24 minutes respectively. Table 5.4b summarises the results and Figure 5.4 illustrates these applications graphically.

Table 5.4b Summary of Terrace Reaction to Storms of Varying Duration

Ref	Intensity (mm/hr)	Total Rainfall (mm)	Volume Increase (l)	Storm Duration (mins)	Time to Stability after 60mm rain (mins)
T1-Rain30d120	30	60	1700	120	114
T1-Benchmark (Benchmark Test)	**60**	**60**	**2821**	**60**	**131**
T1-Rain90d40	90	60	3532	40	137
T1-Rain120d30	120	60	4024	30	142
T1-Rain150d24	150	60	4378	24	145

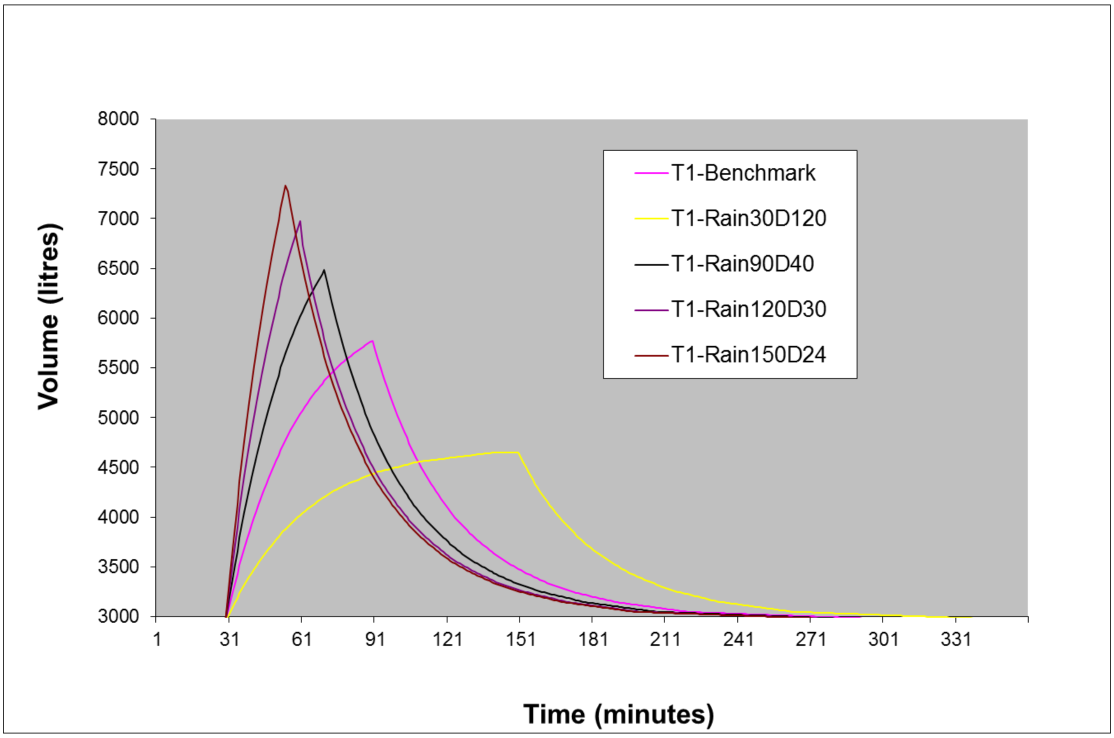


Figure 5.4 Comparison of Terrace Volume when Rainfall Duration is Changed

5.4.4 Comparison of the Impact of Rainfall Intensity to Rainfall Duration

Tables 5.4a and 5.4b, and Figures 5.3 and 5.4 taken together suggest that rainfall intensity is more important than rainfall duration. They show that higher intensities produce a much quicker and stronger reaction from the system for the same amount of rainfall as when intensity is lower, and consequently the time taken to return to equilibrium is greater at the higher intensities, simply because the peak volume attained is greater. In Table 5.4, peak volume at an intensity of 150mm/hr is 4378 litres, more than two and a half times the 1700 litres when intensity is 30mm/hr, even though the same amount of rain has fallen. This is because the constraining influence of the fixed size outflow limits drainage rates. When it rains water volume in the terrace must increase and higher rainfall intensity adds water to the terrace quicker than low intensity rainfall. At lower intensities the drainage outflow to rainfall input ratio is higher and, as the storm is longer, there is more time for drainage during the storm, so even though the same amount of total rainfall is added to the terrace, at lower intensities there is more drainage whilst it is raining so peak volumes are lower.

The importance of intensity over both total duration and total amount of rainfall is confirmed by a further test, comparing the applications reported so far with Application T1-RInfinity. Application T1-RInfinity was of the Standard Storm at an intensity of 60 mm/hr, except that rainfall was not halted after 60 minutes but allowed to continue indefinitely. In this application the system eventually stabilises but obviously at higher levels of throughput. The system stabilised at:

Volume increase: = 3200 l
Depth increase: = 62 mm
Peak outflow: = 107.4 l/min

This shows that even when duration and total rain are indefinite at an intensity of 60 mm/hr the maximum volume level that can be attained is still lower than the volume levels after respectively 40, 30 and 24 minutes rainfall at the higher intensities of 150, 120 or even 90 mm/hr, because at lower intensities the system drains the excess quicker. Indeed, allowing the Standard Storm to continue indefinitely only resulted in a volume increase 379 litres greater than if the storm halted after 60 minutes.

Whilst this shows that rainfall intensity is more important than storm duration and magnitude, it is common sense that a certain threshold of magnitude must be crossed. The above applications (apart from one) model rainfall of at least 60mm and analyse reactions to such storms. If, for instance, only 2mm of rain falls terrace reaction is going to be muted, no matter at what intensity it falls.

5.4.5 Response of the System to Rainfall at Different Rates of Irrigation Inflow

Changing irrigation input introduces several complexities and care must be exercised when comparing the sensitivity of irrigation inflow and rainfall. The following distinguishes between sensitivity to change in irrigation per se and sensitivity to the standard storm at different rates of irrigation inflow. Most importantly, changing irrigation input changes the level at which the system attains equilibrium, which means that a new equilibrium level has to be determined before each model application in order to isolate the response to rainfall. This can be seen in Table 5.5, which summarises results of Model Applications T1-IR0, T1-IR4-Eq, T1-IR6-Eq, T1-IR8-Eq, T1-Eq, T1-IR15-Eq, T1-IR20-Eq, T1-IR25-Eq, T1-IR30-Eq and T1-IR100-Eq, in which the equilibrium position was determined at irrigation inputs varying from zero to 30 l/min and then at an extreme input rate of 100 l/min.

Table 5.5 The Equilibrium Position of the System at Varying Irrigation Input Rates

Ref.	Irrigation Inflow (l/min)	Stable Volume (l)	Stable Depth (mm)	Stable Outflow (l/min)
T1-IR0	0	2500	25	0
T1-IR4-Eq	4	2650	26.5	3
T1-IR6-Eq	6	2750	27.5	5
T1-IR8-Eq	8	2850	28.5	7
T1-Eq	10	2950	29.5	9
T1-IR15-Eq	15	3150	31.5	14
T1-IR20-Eq	20	3350	33.5	19
T1-IR25-Eq	25	3550	35.5	24
T1-IR30-Eq	30	3750	37.5	29
T1-IR100-Eq	100	5850	58.5	99

When there is no rain outflow rates are directly determined by irrigation inflow, the only difference between inflow and outflow being the small amount per minute lost to each of evapotranspiration and seepage (net of return flow). The system stabilises at higher volumes when there is increased inflow because as inflow increases outflow is constrained by the fixed size of the bund outlet. Volume and depth rise until there is sufficient flow height across the outlet to allow flow rates to match those of inflow. The sensitivity of the system to the change in equilibrium before rainfall is applied is considered in Section 5.4.6 and the implications of this are considered in detail in Chapter 8.

Table 5.6 summarises the results of Model Applications T1-IR0, T1-IR4, T1-IR6, T1-IR8, T1-Benchmark, T1-IR15, T1-IR20, T1-IR25, T1-IR30 and T1-IR100, in which the Standard Storm is applied to each of the above equilibrium systems. This series of data shows that once the system is in equilibrium, when it starts to rain the rate of irrigation inflow has little influence on the system, (assuming irrigation inflow remains stable). The differences in absolute levels of peak volume, depth and outflow rates can be clearly seen in Table 5.6 but much of the difference is accounted for by the different levels at which each system stabilised before rainfall started. The increase in volume during the storm is similar for all applications, being slightly less at levels of higher irrigation.

Table 5.6a Terrace Reaction to the Standard Storm when Irrigation Inflow is Varied

Ref.	Irrigation Inflow (l/min)	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l)	Time to Stability (mins)
T1-IR0	0	5431 / 2931	54 / 29	82.7 / 82.7	167
T1-IR4	4	5568 / 2918	56 / 30	89.7 / 86.7	161
T1-IR6	6	5651 / 2851	56 / 29	93.1 / 88.1	151
T1-IR8	8	5703 / 2853	57 / 28	93.1 / 86.1	140
T1-Benchmark	**10**	**5771 / 2821**	**58 / 28**	**96.7 / 87.7**	**131**
T1-IR15	15	5920 / 2770	59 / 27	100.3 / 86.2	125
T1-IR20	20	6074 / 2725	61 / 27	107.4 / 88.4	117
T1-IR25	25	6221 / 2672	62 / 26	111.0 / 87.0	108
T1-IR30	30	6373 / 2623	64 / 26	118.3 / 89.3	98
T1-IR100	100	8268 / 2418	83 / 24	191.1 / 92.1	90

There is greater absolute and percentage increase in water volume in the terrace for applications with lower rates of irrigation input. This is because there is less volume and therefore lower depth of water in the terrace when rainfall starts and, because of the power based relationship between depth increase and outflow increase, less outflow at the start of the storm and less increase in outflow per mm rise in depth. This means that, when a fixed amount of rainfall is introduced at constant rate, for any given time point in the storm outflow rates from a system with a lower equilibrium position are slightly lower than those for a system with a higher equilibrium position throughout the whole application. Consequently, the system drains slightly more slowly and thus retains more water.

This is better illustrated in Figure 5.5, a comparison of volume increase for each application (again, for comparison purposes shown as increase in volume rather than absolute volume). Figure 5.5 reflects the volume increases detailed in Table 5.6 and shows the hydrograph of each of the applications clustered around that of the Benchmark Test, Application T1-Benchmark. Application T1-IR100, for which irrigation inflow was towards the extreme of 100 l/min, is seen to be that with the lowest increase, for the reasons stated above. For further comparison Application T1-Rain120 from Figure 5.3, in which a storm of 120 mm/hr (that is, an increase of 60 mm/hr over the Benchmark Test) was applied to the default environment, is superimposed on figure 5.5. This clearly shows that changes due to differences in irrigation inflow are of lower magnitude compared to changes induced by the rain itself.

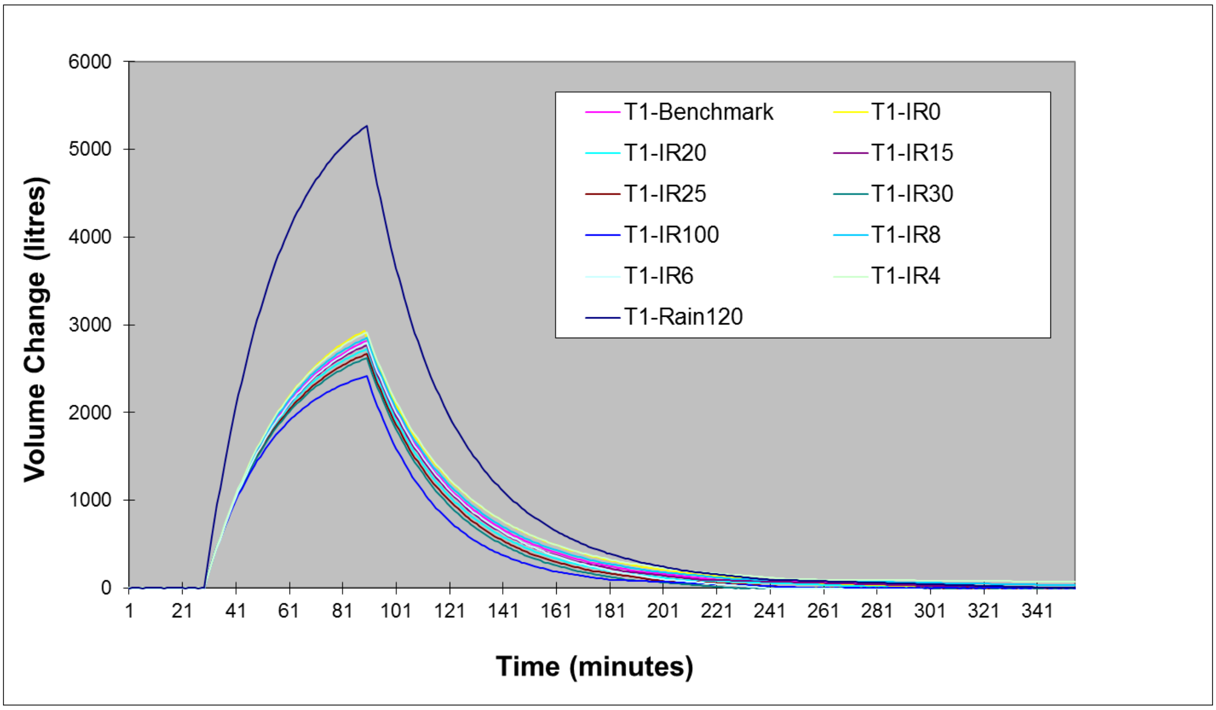


Figure 5.5 Comparison of Terrace Volume Change for Different Rates of Irrigation Inflow

Also of importance when considering irrigation inflow is the time the system takes to regain stability after the storm. This varies from 98 minutes when irrigation input is 30 l/min to 161 and 167 minutes when irrigation is 4 and zero l/min respectively. The differences explained by the non-linear nature of flow across the outlets vis-à-vis the levels at which the system is stabilising. When the equilibrium position dictates stability at a higher volume/depth and therefore higher outflow the system will drain more quickly and regain its stable level quicker. This is particularly seen in the difference between Applications T1-IR30 and T1-IR100, where irrigation inflows are 30 l/min and 100 l/min respectively. Even though there is an extreme increase in inflow rates the time taken to return to the equilibrium position is only increased by 8 minutes. Conversely, at lower stable levels flow rates are less and the system takes longer to attain its equilibrium position. This is particularly so at very low flow rates at which the non-linear effect is very pronounced. Even though the same volume of water has been added to both systems, Application T1-IR8, T1-IR6 and T1-IR4 take 9, 20 and 30 minutes longer to drain than the Benchmark Test though irrigation inflow has only been lowered by 2, 4 and 6 l/min respectively.

This means that, although the effect of irrigation input has been shown to be small (in isolation) during the rainstorm, it can have considerable impact on the falling limb of the hydrograph which, taken together with the different pre and post storm equilibrium positions it dictates, indicates the complexities introduced by full terrace systems, discussed later in the chapter.

5.4.6 The Interaction between Rainfall and Irrigation Inflow

Whilst the purpose of the sensitivity exercise is to review change in each variable in isolation, this has to be considered in the context of the field situation. The above shows that in isolation irrigation inflow is less important than rainfall but, in the field situation, there will be an increase in irrigation inflow when rain starts caused by rain falling directly into the canal and higher on the hillslope. In a real storm the khet system is subject to direct increase in water volume from rainfall and indirect increase in irrigation water also caused by rainfall. Field results reported in Chapters 6 and 7 show that typical irrigation levels increase 3 or 4 fold in even moderate storms and inflow rates of 100 l/min tested in Section 5.4.5 above were recorded.

If irrigation water is increased we have seen that the system needs time to attain a new equilibrium. In reality, if irrigation inflow is increasing because of rainfall both will act simultaneously and the effects cannot be viewed in isolation. In the above applications, care was taken to ensure the system attained a new equilibrium when irrigation was increased. In effect, this is isolating the change brought about by irrigation increase by masking the likely cause of the increase (i.e. rainfall). It is a better replication of the field situation, though a less rigorous test of the sensitivity of individual variables, if the system were not allowed to gain equilibrium prior to comparisons being made between applications.

Table 5.7c, comparing least squares of the various applications, helps to illustrate this. Rainfall intensity is again shown to be most important by this criterion, showing much higher scores than both rainfall duration and irrigation. However, a least squares calculation was also performed for the irrigation tests without allowing the system to first determine a new equilibrium. This provided much higher least squares scores, of the same magnitude as rainfall intensity.

5.4.7 Response of the System to Changes in Evapotranspiration, Seepage and Return Flow

In the KhetFlow Model evapotranspiration, seepage and return flow are all treated as a function of surface area. Evapotranspiration and seepage directly so, return flow indirectly as a percentage of seepage (return flow is seepage returning to the surface in the terrace below, seeping out of the soil face of the riser). Not all seepage will become return flow, although return flow could also include a fraction of returning seepage from higher on the hillslope. Whilst evaporation is related to the water/air surface interface and seepage is related to the water/soil interface, in this system these two surface areas are virtually of identical size because the shallow water depth and vertical sides of the ‘pond’.

Seepage and evapotranspiration are losses from the terrace, return flow a gain of water to the terrace. Because each is reduced to a process value measured in ml/m^2/min for a particular terrace or system it is valid to net the process values to one figure to apply to the model.

In is not suggested that in the physical world area is the only component of these processes. For instance, evapotranspiration is also a function of crop density; seepage is also a function of the head of water and return flow is only indirectly related to area as a percentage of seepage from the terrace above. Additionally, not all seepage will become return flow as there are losses to depths that bypass the downslope terraces and return flow could also include a fraction of returning seepage from higher on the hillslope. However, at the scale required for this study each of these will only make a small difference to the rate of a minor variable and the approach taken provided sufficient accuracy, particularly as gains from return flow mitigate losses from evapotranspiration and seepage.

The model was tested to ensure that exactly the same results were obtained if these three variables were set with high values as when they were set with low values, provided the net figure was the same, eg. evaporation 50 ml/m^2/min, seepage 200 ml/m^2/min, return flow 75% at 150 ml/m^2/min, a net figure of 100 ml/m^2/min; produced the same results as evaporation 10 ml/m^2/min, seepage 180 ml/m^2/min, return flow 50% at 90 ml/m^2/min, the same net figure of 100 ml/m^2/min. This was the case and it was thus legitimate to combine these three variables for model applications.

Evapotranspiration, Seepage and Return Flow were modelled to the extremes of ranges likely in the field (as reported in Section 4.5). Changes to these variables had little effect on peak values during the storm but had some influence on the falling limb. Slightly complex reactions were noted, as is discussed below. As with changes in irrigation, new equilibrium values for the system had to be established before the Standard Storm was applied. The results from these applications are summarised in Table 5.6b and illustrated by the hydrographs in Figure 5.6.

Table 5.6b Summary of Terrace Reaction to the Standard Storm when Evapotranspiration, Seepage and Return Flow are varied.

Ref.	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l)	Time to Stability (mins)
T1-Eq	**2950**	**29.5**	**9.0**	
T1-Benchmark	**5771 / 2821**	**57.7 / 28.2**	**96.7 / 87.7**	**131**
T1-ESR0-Eq	3050	30.5	10.0	
T1-ESR0	5806 / 2754	58.0 / 27.5	96.7 / 86.7	152
T1-Evap20-Eq	2850	28.5	7.5	
T1-Evap20	5722 / 2872	57.2 / 28.7	93.7 / 85.7	153
T1-Seep333	4784 / 1784	47.8 / 17.8	62.5 / 52.5	----

Model Application T1-ESR0 tests the system when the rates for Evapotranspiration, Seepage and Return Flow are all set to zero. Application T1-ESR0-Eq first established an equilibrium position for such a system, this being at slightly higher volume levels than the equilibrium for the Benchmark Test because, by definition, terrace losses are lower; and T1-ESR0 applied the Standard Storm to this environment.

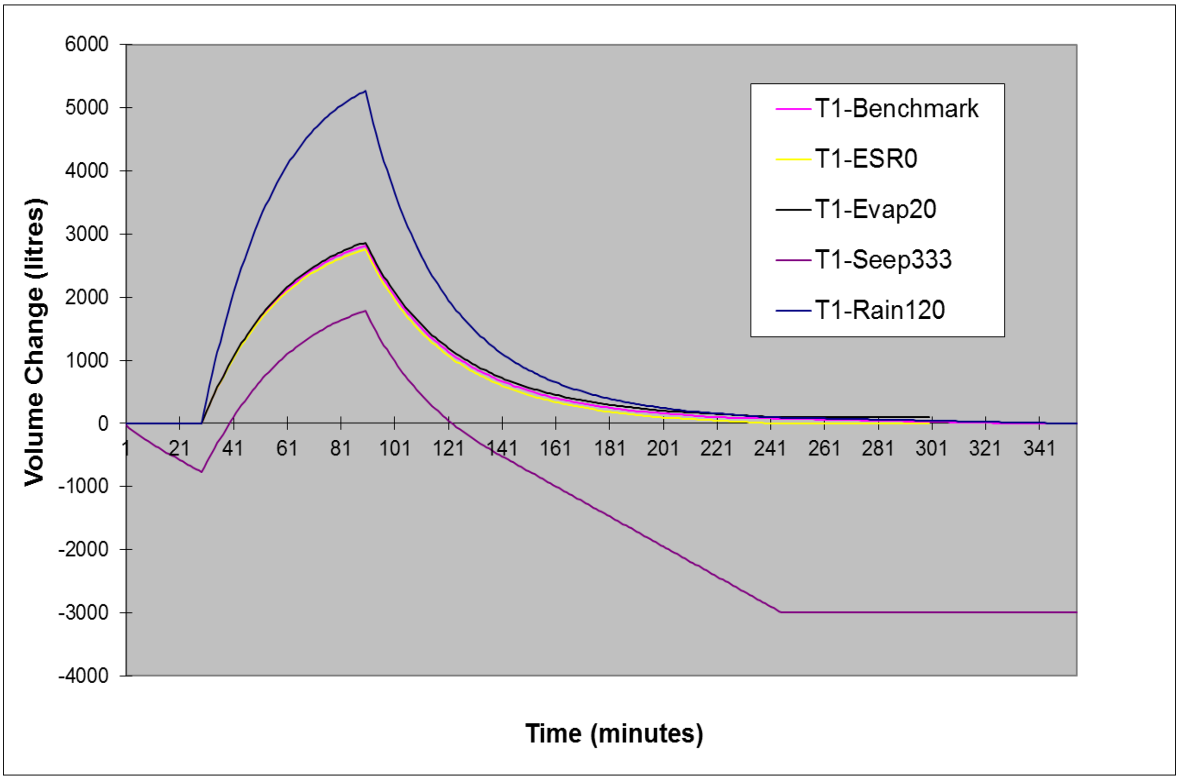


Figure 5.6 Comparison of Terrace Volume Change when Evapotranspiration, Seepage and Return Flow Rates are Changed

Comparison with the Benchmark Application T1-Benchmark shows little difference as regards volume change. Absolute volume peak is slightly higher because terrace losses are lower but volume increase was slightly lower because of the interaction of different initial levels of stability and power based increase in outflow rates. The time to return to stability was 21 minutes longer because there are no losses from evapotranspiration and seepage to assist draining.

In Model Application T1-Evap20 the environment was returned to that of the Benchmark test, Application T1-Benchmark, except that evapotranspiration was set to 20 ml/m^2/min. This is equivalent to 26.7 mm per day, considered to be at the extreme of the possible range for this sub-tropical area. There is little difference between this application and that of T1-ESR0 as regards peak and increased water volume and outflow rates but, when compared to T1-ESR0 and the Benchmark Test T1-Benchmark, the complexity of interactions within the system is illustrated. As there are greater losses from within the terrace from the combination of evapotranspiration and seepage (25 ml/m^2/min) than the Benchmark Test (10 ml/m^2/min) and from Application T1-ESR0 (0 ml/m^2/min) it would be expected that reaction to rainfall input would be slightly diminished. This is indeed the case when considering peak values. However, the increase in volume/depth of water in the terrace is actually greater in Application T1-Evap20, even though losses are higher. This is explained by the power based reaction to the lower volume of the equilibrium position in Application T1-Evap20 (because there are higher losses) which means that when volume initially increases at the onset of the storm the rate of outflow increase will be lower than for the other two applications. As less water is being lost, volume and depth increase are greater.

This is also reflected in the time taken to return to stability, which increases from 131 mins to 152 mins if Application T1-ESR0 is compared to the Benchmark Test, because drainage takes longer as there are no losses from evapotranspiration and seepage. It would therefore be expected that increasing combined losses from evapotranspiration and seepage from 10 ml/m^2/minto 25 ml/m^2/minin Application T1-Evap20 would reduce the time to return to stability. However, faster draining because of higher loss levels is cancelled out because the system has to drain to a lower level in application T1-Evap20 and the decrease in flow per mm drop in flow height is less. The time taken to revert to stability is greater than in the Benchmark Test when combined losses are 10 ml/m^2/min; and virtually the same as in Application T1-ESR0 when there were no evapotranspiration and seepage losses at all.

Whilst these results show that the reactions in the system are complex they are again put into context when compared with the reaction of the system to changes in rainfall. Figure 5.6 shows how similar the increase in volume for Applications T1-ESR0 and T1-Evap20 are to the Benchmark Test and how the impact of rainfall, again illustrated by Application T1-Rain120, is much more important.

Model Application T1-Seep333 is also shown on Figure 5.6. For this application seepage was increased to the highest field rates experienced, which represents a much higher loss of water than from evapotranspiration. On one small set of terraces monitored in the field, drainage rates from seepage, seemingly because of high macro-pore density, were approximately 20mm per hour. These terraces needed constant heavy irrigation to remain ponded and drained quickly when irrigation water was diverted to other terrace systems. Such terraces are closer in character to rainfed bariland than true khet terraces and more difficult to manage, as the model helps illustrate. However, they were viable for farming rice when irrigation water could be relied on virtually constantly. (The rice varieties grown in the monsoon period are normally grown in ponded water but local farmers confirmed that these varieties are viable even when water cannot be ponded, provided the soil does not become too dry and some periods of ponding are achieved).

Losses of 20mm per hour equate to 333 ml/m^2/min. At this rate it is not possible to determine an equilibrium position because stability in the system is not possible (the system simply dries out). In such a situation, without rainfall - as is illustrated in Model Application T1-Seep333a, losses from the terrace are such that the terrace drains to below the clearance level of the outlet, thus stopping flow, in 16 minutes and the terrace drains completely in a further 107 minutes. When the Standard Storm is introduced, Model Application T1-Seep333, reaction is severely muted because of the high seepage losses. Flow stops only 49 minutes after rain ceases and again the terrace is drained in a further 107 minutes.

Whilst this situation did reflect a field situation it was a highly unusual one and does not reflect a true khet system. The rate of seepage used in the Benchmark Test, 5 ml/m^2/min is much more the norm in the field. However, this application does serve to illustrate the narrow range of variables within which the system can operate as viable khetland and how quickly the system breaks down outside the viable range. This is considered further later in the chapter when khet systems of 25 terraces are examined and the design of further research is explained.

5.4.8 Response of the System to Variances in Terrace Characteristics

Changes in process rates on a single terrace have been examined but terrace reaction will also be modified by variations in terrace characteristics. Changing the size of the terrace, the size, shape or number of the inflows and outflows and amending water flow across the terrace will all alter terrace response and these situations were tested as part of the sensitivity exercise. However, as with the tests considering evapotranspiration, seepage and return flow, there is a need to ensure that the tests reflect realistic situations and, indeed, many of the tests conducted here were purely academic applications of the model for the purposes of the sensitivity exercise. It is reasonable to test the strength of reaction to changes in variables for a single terrace but in reality, when considered over the length of multi-terrace khet sub-systems that khet hillslopes are composed of, the need to maintain a water balance throughout the overall system, and the fact that these tests disrupt that water balance and quickly cause system failure either because the terraces overflow or because the system cannot maintain flow and drains, means that these are theoretical applications that would never occur in the field.

Simple examples illustrate. If the size of the terrace is increased without increasing the size of the outflow or increasing the number of outflows higher levels of water would be retained in the terrace (in fact, the terrace is likely to overflow). Similarly, if the size of the terrace is reduced without a pro rata reduction in outflow capability, the terrace will drain. In reality, through a process of trial and error during the building and operation of the terraces, the farmer would set outflow size and number proportionate to the terrace size to keep the system in balance.

Adjusting the size of the outflow when the terrace area remains static will have the same outcome as changing the area and leaving outflow capability static; overflow if the outflow capability is reduced, the terrace draining if it is increased. Restricting flow across the terrace is a realistic situation to test but, as with the tests that varied evapotranspiration, seepage and return flow, the flow restriction must remain within a reasonable range.

Sensitivity tests were conducted on the single terrace system whereby the size of the terrace was varied, the size of the outflow was varied, the shape of the outflow was varied and flow across the terrace was restricted. The following section summaries the sensitivity of variable in a one terrace khet system and of the tests varying the terrace characteristics are reported there for the purpose of comparison. The need to maintain a water balance in the system and the implications of that are considered again later in the chapter when the sensitivity of multi terrace systems is examined and the deployment of the KhetFlow model in this research is evaluated. This is also considered further in Section 8.3 when appropriate situations in which to deploy the model for experimental purposes are selected.

5.4.9 Summary of Sensitivity of Variables in a One Terrace System

When variables are set within acceptable ranges and situations are tested that realistically reflect field conditions ***the most important variable acting on the khet system is rainfall intensity, particularly when coupled with irrigation inflow, of which it is the main component during a storm.***

Three criteria were used to compare the sensitivity of a variable when tested by using the benchmark test of a standard storm applied to a standard khet system:

1. Maximum increase, in absolute terms, in the volume of water in the terrace over that of the pertaining equilibrium position, summarised in Table 5.7a - Ranking of Sensitivity Tests by Volume Increase;
2. Time taken for the system to return to the pertaining pre-storm equilibrium position after rainfall has ceased, summarised in Table 5.7b - Ranking of Sensitivity Tests by Time to Stability;
3. Sum of squares differences between the hydrograph of the benchmark application and that of the test application, summarised in Table 5.7c - Ranking of Sensitivity Tests by Least Squares Scores.

The following should be taken into account whilst comparing model applications:

a). It is necessary for the system to gain an equilibrium position before many applications so that the amended variable is isolated. A lower equilibrium start point for one test could lead to the same storm having less impact on volume in absolute terms but greater impact in percentage terms. Changing some variables changes the system in such a way that it eventually stabilises at a new equilibrium, which makes comparison difficult.

b). The time the system takes to retain its pre-storm position is important but longer durations can be the result of activities that obviously cause lower impact. For instance, reducing or closing canal inflow before the Standard Storm is applied lessens impact but actually greatly increases duration of impact. This is because the non-linear nature of flow means that at low flow levels it takes a long time to regain the last few millimetres of the pre-storm position.

c). The least squares method compares the whole hydrograph but small differences over a long time period may introduce bias when compared to high, short term impacts.

Nonetheless, the impact of rainfall intensity stands out. This is clearly seen in Tables 5.7a and c. In both of these tables the applications that increase rainfall intensity and/or volume are at the top of the rankings, with applications representing the most intense rain having by far the greatest impact. Compared to applications of the two most intensive rain events, which increase volumes by 228% and 187% respectively, most applications make little impact on the system. This is reflected in the comparison of least squares. The only comparable situations to rainfall impact, explained in section 5.4.6, is when rainfall is added to irrigation inflow. In this situation, as can be seen in the least squares table, the impact of rainfall can be more than doubled.

Comparing the times the system took to regain stability is less clear-cut. Even very high total volume increases do not have great impact. The highest volume increase of 228%

when rainfall intensity was increased to 150 mm/hr only required an extra 25 minutes to recover stability, an increase in time of 19%. The applications that had most impact by this criterion were those that restricted flow (by the nature of the test, this should be expected). But these, such as narrowing the outflow, restricting flow by 25% or cutting off irrigation, were unlikely to occur in the field, especially during a storm. Otherwise, impact was less than 20% different to that of the benchmark. Figures 5.7 and 5.8 show comparisons of the absolute volume and volume increase for all the single terrace applications.

It should be remembered that these tests were conducted on a one terrace system to ascertain the most sensitive variables. When the complexities of larger systems are introduced, as below, the impact of duration, as effects are propagated down the system, is more important. The non-linear, power based nature of reaction has been noted from the applications, which will also complicate reaction in multi-terrace systems. Also, each isolated reaction is reasonably simple to explain but the combination of all the reactions is more complex. Again, this will become more complicated on larger systems.

It has become evident, from tests on even just one terrace, that there is a narrow band of acceptable values for variables and that constraints are placed on the system either by reasonable rates for process variables or by what is reasonable in the field. Outside of this narrow range of process rates the system breaks down.

Table 5.7a Ranking of Sensitivity Tests by Volume Increase

Rank	Reference	Application	Volume Increase	% of Benchmark	Stability time	% of Benchmark	Sum of Squares	Including Change in Equilibrium
1	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	6427	228	156	119	867573	
2	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	5269	187	150	115	399185	
3	T1-Rain150d24	Rain 150 mm/hr - Duration = 24 mins	4378	155	145	111	200983	
4	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	4067	144	143	109	103585	
5	T1-Rain120d30	Rain 120 mm/hr - Duration = 30 mins	4024	143	142	108	138271	
6	T1-Narrow	Narrow Outflow, standard storm	3873	137	234	179	181697	
7	T1-Rain90d40	Rain 90 mm/hr - Duration = 40 mins	3532	125	137	105	60708	
8	T1-Flow90	Set Flow coefficient to 75%, Standard storm	3371	119	170	130	7686	
9	T1-Rinfinity	Continuous rain, new stability achieved	3201	113	161	123	8190952	
10	T1-Vweir	V-shaped Weir, standard storm	3174	113	210	160	40225	
11	T1-Flow75	Set Flow coefficient to 90%, Standard storm	3051	108	165	126	39982	
12	T1-IR0	Canal inflow closed, Qin zero - Standard storm	2931	104	167	127	34607	329226
13	T1-IR4	Reduce Qin to 4ml/min - Standard storm	2918	103	161	123	3067	66395
14	T1-IR6	Reduce Qin to 6ml/min - Standard storm	2901	103	151	115	4675	26905
15	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	2872	102	153	117	781	
16	T1-IR8	Reduce Qin to 8ml/min - Standard storm	2853	101	140	107	405	7659
17	T1-Clear50	Change weir clearance, Standard Storm	2821	100	131	100	0	
18	T1-Benchmark	Benchmark Test	2821	100	131	100	0	
19	T1-IR15	Increase Qin to 15ml/min - Standard storm	2770	98	125	95	312	36930
20	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	2756	98	152	116	1274	
21	T1-IR20	Increase Qin to 20ml/min - Standard storm	2725	97	117	89	1333	145408
22	T1-IR25	Increase Qin to 25ml/min - Standard storm	2672	95	108	82	3391	324122
23	T1-IR30	Increase Qin to 30ml/min - Standard storm	2623	93	98	75	6216	575198
24	T1-CP125	Set Change Parameter to 125%, Standard storm	2618	93	n/a	n/a	19282	
25	T1-IR100	Increase Qin to 100ml/min - Standard storm	2418	86	139	106	18624	8041414
26	T1-CP110	Set Change Parameter to 110%, Standard storm	2375	84	n/a	n/a	4495	
27	T1-Seep333	Evap = 5, Seepage = 333, Ret.flow = 0	1784	63	n/a	n/a	6773230	
28	T1-Wide	Inc. Outflow, standard storm	1764	63	61	47	93613	
29	T1-Rain30d120	Rain 30 mm/hr - Duration = 120 mins	1700	60	114	87	160899	
30	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	1485	53	109	83	118834	

Table 5.7b Ranking of Sensitivity Tests by Time to Stability

Rank	Reference	Application	Stability time	% of Benchmark	Volume Increase	% of Benchmark	Sum of Squares
1	T1-Narrow	Narrow Outflow, standard storm	234	179	3873	137	181697
2	T1-Vweir	V-shaped Weir, standard storm	210	160	3174	113	40225
3	T1-Flow90	Set Flow coefficient to 75%, Standard storm	170	130	3371	119	7686
4	T1-IR0	Canal inflow closed, Qin zero - Standard storm	167	127	2931	104	34607
5	T1-Flow75	Set Flow coefficient to 90%, Standard storm	165	126	3051	108	39982
6	T1-Rinfinity	Continuous rain, new stability achieved	161	123	3201	113	8190952
7	T1-IR4	Reduce Qin to 4ml/min - Standard storm	161	123	2918	103	3067
8	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	156	119	6427	228	867573
9	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	153	117	2872	102	781
10	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	152	116	2756	98	1274
11	T1-IR6	Reduce Qin to 6ml/min - Standard storm	151	115	2901	103	4675
12	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	150	115	5269	187	399185
13	T1-Rain150d24	Rain 150 mm/hr - Duration = 24 mins	145	111	4378	155	200983
14	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	143	109	4067	144	103585
15	T1-Rain120d30	Rain 120 mm/hr - Duration = 30 mins	142	108	4024	143	138271
16	T1-IR8	Reduce Qin to 8ml/min - Standard storm	140	107	2853	101	405
17	T1-IR100	Increase Qin to 100ml/min - Standard storm	139	106	2418	86	18624
18	T1-Rain90d40	Rain 90 mm/hr - Duration = 40 mins	137	105	3532	125	60708
19	T1-Clear50	Change weir clearance, Standard Storm	131	100	2821	100	0
20	T1-Benchmark	Benchmark Test	131	100	2821	100	0
21	T1-IR15	Increase Qin to 15ml/min - Standard storm	125	95	2770	98	312
22	T1-IR20	Increase Qin to 20ml/min - Standard storm	117	89	2725	97	1333
23	T1-Rain30d120	Rain 30 mm/hr - Duration = 120 mins	114	87	1700	60	160899
24	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	109	83	1485	53	118834
25	T1-IR25	Increase Qin to 25ml/min - Standard storm	108	82	2672	95	3391
26	T1-IR30	Increase Qin to 30ml/min - Standard storm	98	75	2623	93	6216
27	T1-Wide	Inc. Outflow, standard storm	61	47	1764	63	93613

Table 5.7c Ranking of Sensitivity Tests by Least Squares Scores

Rank	Reference	Application	Volume Increase	Including Change in Equilibrium	Stability time	% of Benchmark	Sum of Squares	% of Benchmark
1	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	867,573		6427	228	156	119
2	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	399,185		5269	187	150	115
3	T1-Rain150d24	Rain 150 mm/hr - Duration = 24 mins	200,983		4378	155	145	111
4	T1-Narrow	Narrow Outflow, standard storm	181,697		3873	137	234	179
5	T1-Rain30d120	Rain 30 mm/hr - Duration = 120 mins	160,899		1700	60	114	87
6	T1-Rain120d30	Rain 120 mm/hr - Duration = 30 mins	138,271		4024	143	142	108
7	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	118,834		1485	53	109	83
8	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	103,585		4067	144	143	109
9	T1-Wide	Inc. Outflow, standard storm	93,613		1764	63	61	47
10	T1-Rain90d40	Rain 90 mm/hr - Duration = 40 mins	60,708		3532	125	137	105
11	T1-Vweir	V-shaped Weir, standard storm	40,225		3174	113	210	160
12	T1-Flow75	Set Flow coifficient to 90%, Standard storm	39,982		3051	108	165	126
13	T1-IR0	Canal inflow closed, Qin zero - Standard storm	34,607	329,226	2931	104	167	127
14	T1-CP125	Set Change Parameter to 125%, Standard storm	19,282		2618	93	n/a	n/a
15	T1-IR100	Increase Qin to 100ml/min - Standard storm	18,624	8,041,414	2418	86	139	106
16	T1-Flow90	Set Flow coifficient to 75%, Standard storm	7,686		3371	119	170	130
17	T1-IR30	Increase Qin to 30ml/min - Standard storm	6,216	575,198	2623	93	98	75
18	T1-IR6	Reduce Qin to 6ml/min - Standard storm	4,675	26,905	2901	103	151	115
19	T1-CP110	Set Change Parameter to 110%, Standard storm	4,495		2375	84	n/a	n/a
20	T1-IR25	Increase Qin to 25ml/min - Standard storm	3,391	324,122	2672	95	108	82
21	T1-IR4	Reduce Qin to 4ml/min - Standard storm	3,067	66,395	2918	103	161	123
22	T1-IR20	Increase Qin to 20ml/min - Standard storm	1,333	145,408	2725	97	117	89
23	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	1,274		2756	98	152	116
24	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	781		2872	102	153	117
25	T1-IR8	Reduce Qin to 8ml/min - Standard storm	405	7,659	2853	101	140	107
26	T1-IR15	Increase Qin to 15ml/min - Standard storm	312	36,930	2770	98	125	95
27	T1-Clear50	Change weir clearance, Standard Storm	0		2821	100	131	100
28	T1-Benchmark	Benchmark Test	0		2821	100	131	100
	T1-Rinfinity	Continuous rain, new stability achieved	8,190,952		3201	113	161	123
	T1-Seep333	Evap = 5, Seepage = 333, Ret.flow = 0	6,773,230		1784	63	n/a	n/a

Figure 5.7 Comparison of Absolute Volume for all Single Terrace Applications

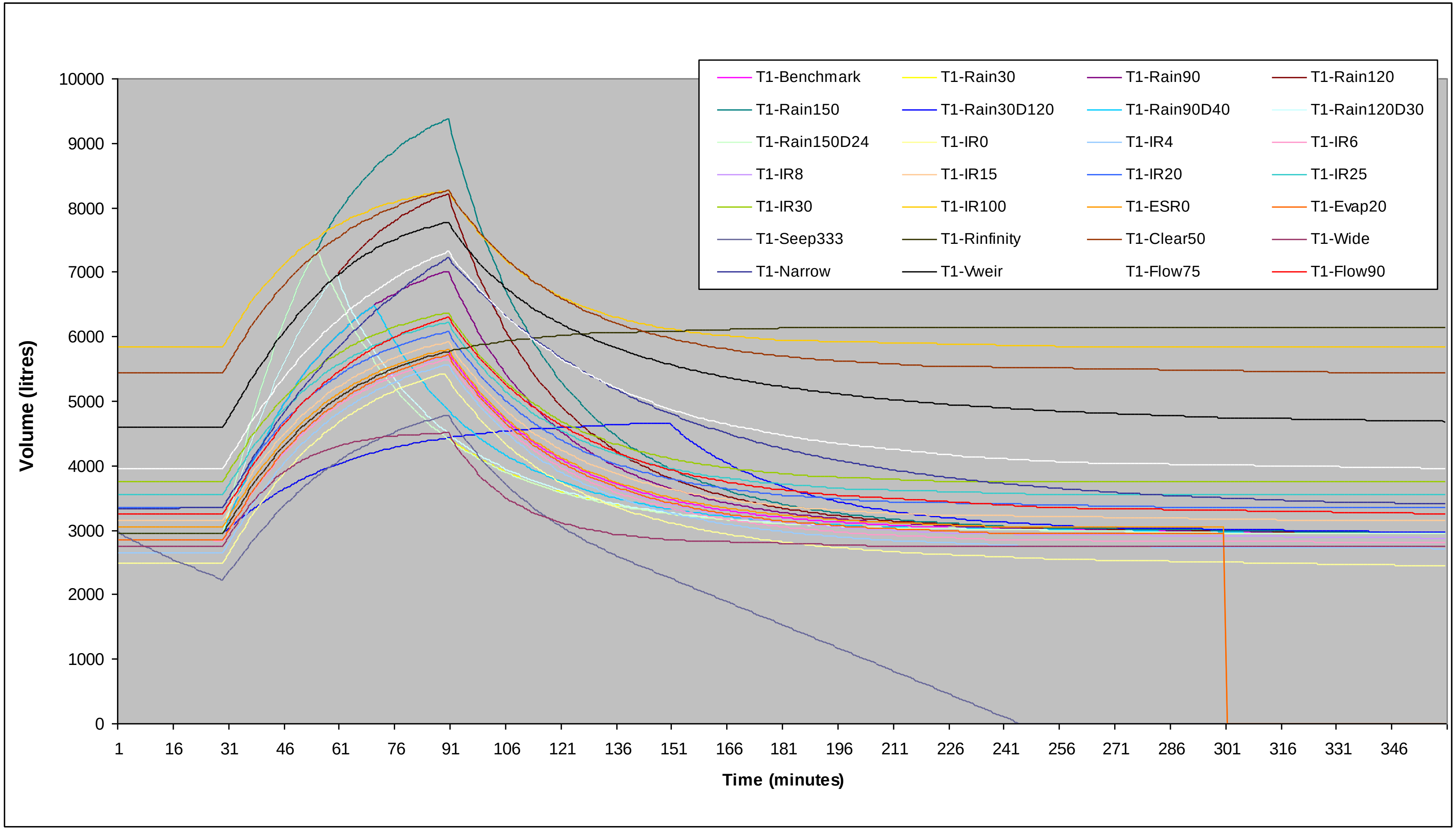
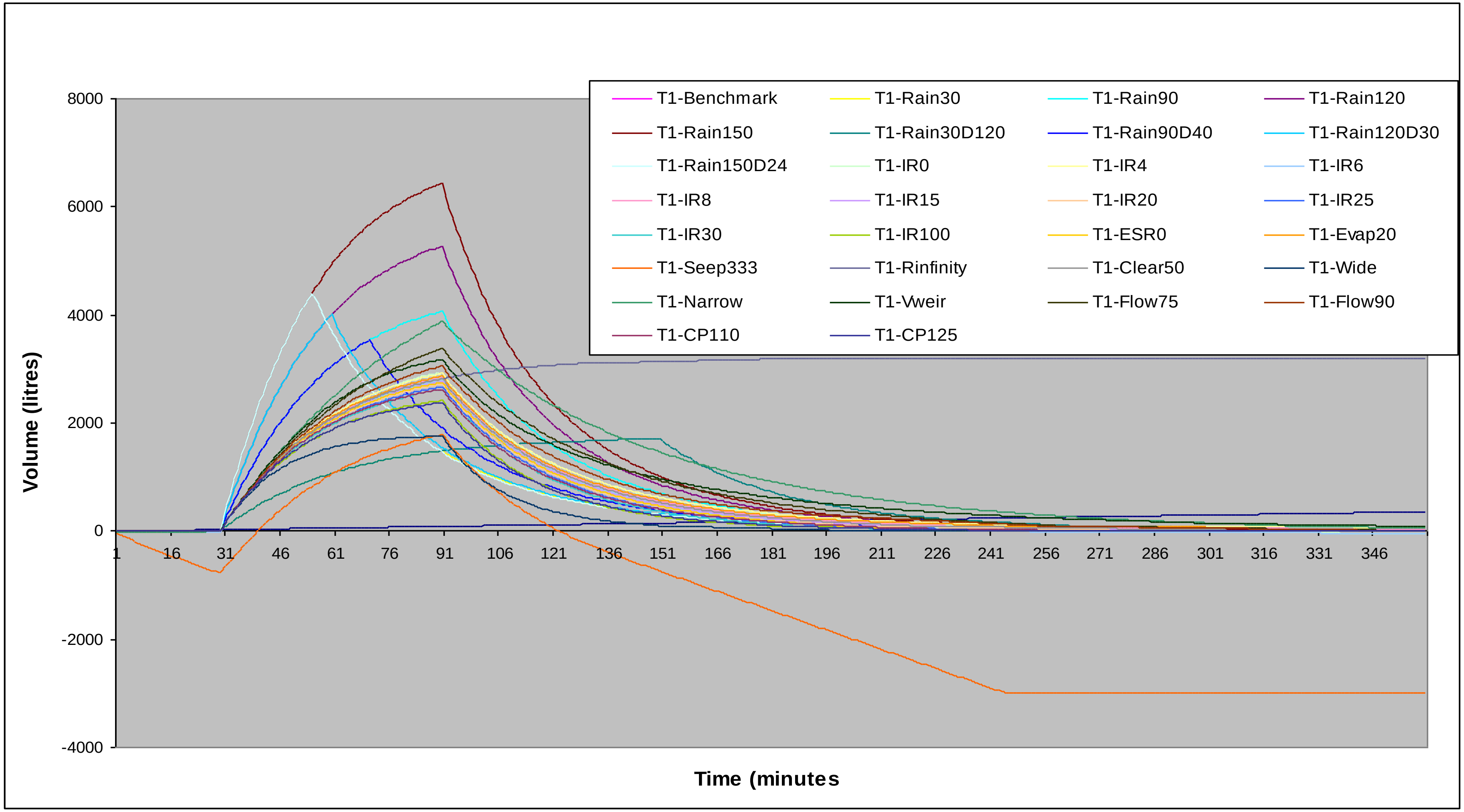


Figure 5.8 Comparison of Volume Change for all Single Terrace Applications



5.5 Sensitivity Analysis of Multiple Terrace Systems

5.5.1 Complexities introduced by Multiple Terraces

In a multi-terrace system the sensitivity of individual terraces, when viewed in isolation, will be as described above as each reacts to the balance of inputs and outputs in accordance with the continuity equation. However, whilst simulating the reaction on the top terrace of such a system is effectively the same as simulating the processes in a single terrace system, the behaviour of terraces lower in the system is more complex. For instance, it would be reasonable to expect that there would be a greater increase in the volume of water in the lower terraces as water propagates through the system and that a time lag would be introduced during the falling limb as terraces lower in the slope continue to receive water draining from higher terraces after rain has ceased. In multi-terraced systems, as discussed in Chapter 2, there should be layered cumulative effects.

In this section sensitivity analysis is undertaken on two linearly linked systems, one of four terraces to illustrate the behaviour of linked terraces in a simple system, and one of twenty five terraces, more typical of the situation on Nepali hillsides, where the number of ‘layers’ or ‘drops’ of terraces between irrigation canals is usually between 10 and 30.

For the purpose of sensitivity analysis, all the terraces in these linked systems are the same size as in the single terrace system, 100 m^2 and irrigation inflow, evapotranspiration, seepage and return flow are where possible the same as for the Benchmark Test in Application T1-Eq/T1-Benchmark (see Table 5.1) to allow comparison in the same environment. However, as is explained below, adjustments had to be made when working with the twenty five terrace system.

Tests are first conducted on a four terrace khet system but not all the tests undertaken on the single terrace system were repeated as the purpose here is only to illustrate the complexities introduced by multiple terraces. The tests on a single terrace have shown that terraces react mostly to rainfall intensity linked with irrigation inflow. The same will be true of individual terraces in a multi-terrace system when viewed in isolation and there was nothing to be gained repeating tests that simply illustrate magnitude of change. The purpose here is to repeat representative tests of varying process rates to examine the complications introduced by linked terrace systems and illustrate how change is extrapolated through these systems. Tests where terrace characteristics are changed were not conducted on the four terrace system but are considered further when experimenting with the twenty five terrace system, below and in Chapter 8.

5.5.2 System of Four Linear Terraces - Establish Stability and Apply Standard Test

Using the process rates detailed in Table 5.1, Model Application T4-Eq determined the equilibrium position of the four terraces reported in Table 5.8.

Table 5.8 Equilibrium Position of Four Terrace System

Terrace	Volume (l)	Depth (mm)	Outflow (l/min)	Outflow ht (mm)
1	2950	29.5	9000	4.5
(identical to Application T1-Eq)				
2	2949	29.5	8000	4.5
3	2851	28.5	7000	3.5
4	2849	28.5	6000	3.5

The equilibrium position of terrace 1 is the same as for the single terrace in Application T1-Eq. The equilibrium position of each of the terraces below that is at lower volumes and lower flows because water is extracted from the system when it is lost to seepage and evapotranspiration as it traverses each terrace.

Model Application T4-Benchmark illustrates the reaction of the system when the Standard Storm is applied to this equilibrium position. This Application was then used as the Benchmark Test by which to consider other applications on the four terrace system.

Even though there are only four terraces in the system the increase in volumes as water cascades from one terrace to the next is clearly seen and the magnitude of the increase is substantial. Table 5.9 shows that the total increase in volume by the end of the storm in terraces 1 to 4 is 2819, 4478, 5473 and 5883 litres respectively. Increases in depth, outflow and flow height over the weir are similarly cumulative.

After each minute of the storm the volume of water in each terrace increases because of rainfall into the terrace and this consequently increases outflow. Increased outflow from one terrace is increased inflow to the terrace below, so the volume in terraces lower in the system is increasing not just from rainfall input but also because of increased input from above.

Table 5.9 Standard Storm applied to Four Terrace System

Terrace	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l/min)	Peak Outflow ht. (mm)	Time to Stability (min)
1	5771 / 2819	58 / 28	96.7 / 87.7	33	131
(identical to Application T1-Benchmark)					
2	7427 / 4478	74 / 45	155.9 / 147.9	49	184
3	8324 / 5473	83 / 54	191.1 / 184.1	58	287
4	8732 / 5883	87 / 59	207.2 / 201.2	62	315

The effect is cumulative down the system. Thus, the increase in volume/outflow is greater in terrace 2 than in terrace 1. As inflow to terrace 3 is consequently greater than terrace 2, so increase in volume/outflow is greater in terrace 3 than terrace 2; and so on through the system. A snapshot taken after 15 minutes of the storm illustrates this. At this point the outflow from terrace 1/inflow to terrace 2 has increased from 9 l/min to 43 l/min, from terrace 2 to terrace 3 from 8 l/min to 49 l/min and from terrace 3 to terrace 4 from 7 l/min to 53 l/min; respective increases of 34, 41 and 46 l/min progressively down the system.

By the end of the storm outflows/inflows increased to even greater levels. The inflow to terrace 2 from terrace 1 is 96.7 l/min; to terrace 3 from terrace 2 is 115.9 l/min; to terrace 4 from terrace 3 is 191.1 l/min; and the outflow from terrace 4 is 207.2 l/min. In the last minute of the storm terrace 1 is still receiving comparatively very little inflow (10 l/min from irrigation) but terraces 3 and 4 are receiving more water from inflow from terraces above than from rainfall, which at the intensity of the Standard

Storm is providing 100 l/min. So, in a similar manner to the single terrace system where increased irrigation inflow reinforced the terrace reaction to rainfall during the storm, in the terraces lower in the system inflow from above substantially reinforces reaction to rainfall, even though (for the purpose of this test) irrigation inflow to the top terrace was controlled and constant.

Application T4-Benchmark also illustrates the extended time the system takes to drain to its pre-storm equilibrium position. There are two reasons for this. There is more water in the lower terraces when rainfall stops so it takes longer to drain the increased volume, and even after rainfall has ended the lower terraces will continue to receive enhanced inflows as higher terraces drain. This is illustrated by the position of the system at the point the top terrace completes draining and re-established equilibrium. Terrace 1 stabilises in 131 minutes (as in Application T1-Eq). At that time terraces 2, 3 and 4 still have excesses of 355, 923 and 1815 litres, respectively, and terrace 4 is still receiving water from above at 34 l/min, compared to 7 l/min before the storm. Terrace 4, only three levels down from the top terrace of this small system, takes over 3 hours longer to drain than terrace 1 and this is indicative of the long lags introduced into field systems, as is seen in later sections.

5.5.3 Response of a Four Terrace System to Variation in Rainfall

Model Applications T4-Rain30 and T4-Rain120 examine the four terrace system when rainfall is, respectively, decreased and increased. Tables 5.10 and 5.11 summarise the results. In both these applications the equilibrium position before rainfall was as Application T4-Eq.

Table 5.10 Standard Storm applied, but rainfall intensity reduced to 30 mm/hr

Terrace	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l/min)	Peak Outflow ht. (mm)	Time to Stability (mins)
1	4435 / 1485	44 / 14	49.6 / 40.6	19	109
2	5270 / 2321	53 / 24	75.9 / 67.9	28	159
3	5667 / 2816	57 / 28	93.2 / 86.2	32	263
4	5816 / 2967	58 / 30	96.7 / 90.6	33	288

Table 5.11 Standard Storm applied, but rainfall intensity increased to 120 mm/hr

Terrace	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l/min)	Peak Outflow ht. (mm)	Time to Stability (mins)
1	8219 / 5268	82 / 52	187.2 / 178.2	57	150
2	11483 / 8534	115 / 86	325.1 / 317.1	90	205
3	13423 / 10572	134 / 105	409.8 / 402.8	109	309
4	14404 / 11555	144 / 116	455.7 / 449.7	119	337

The pronounced influence of rainfall when propagated through a multi-terrace system is illustrated by comparison of tables 5.9, 5.10 and 5.11. The peak increase to the lowest terrace was 11,555 litres when rainfall was 120 mm/hr, compared to only 5883 litres when the Standard Storm was applied in application T4-Benchmark and only 2,967 litres when rainfall was 30 mm/hr, values almost directly proportional to the increase in rainfall. The time water takes to completely drain from the system (when terrace 4 returns to equilibrium) is, as expected, also longer in more intense rain - 337 minutes, and shorter in less intense rain - 288 minutes, although the degree of variation is less and the time taken for a terrace to drain changes only slightly with varied rain input. This is attributed to the non-linear nature of flow across the outflow and the increased time taken to drain at lower volumes.

5.5.4 Response of a Four Terrace System to Variation in Evapotranspiration and Seepage

As for the single terrace system, changes within the range of likely values for evapotranspiration and seepage have relatively little impact on water storage in the system, compared to the benchmark. This is illustrated by Model Application T4-ESR0, in which the values of evapotranspiration, seepage and return flow were set to zero and the Standard Storm is applied to the system.

Table 5.12 Evapotranspiration, Seepage and Return Flow are nil, Standard Storm

Terrace	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l/min)	Peak Outflow ht. (mm)	Time to Stability (mins)
1	5796 / 2796	58 / 28	96.7 / 86.7	33	153
2	7487 / 4487	75 / 45	159.8 / 149.8	50	217
3	8420 / 5420	84 / 54	195.1 / 185.1	59	273
4	8859 / 5859	89 / 59	215.3 / 205.3	64	327

The change in water volume during this application is very similar to those for Application T4-Benchmark, peak increase in volume for the lowest terrace is 5,859 litres, compared with 5,883. The time taken to regain stability is only 12 minutes longer at 327 minutes, which is only a slight increase but is noteworthy if compared to an increase of only 22 minutes in T4-Rain120, when approximately twice the volume of water was added to the terrace.

Further applications that increase evapotranspiration and seepage within reasonable bounds had similarly minor effects compared to the benchmark. Increasing seepage to the possible high field value of 20mm per hour reduced peak values and caused all terraces to quickly drain but this was thought unrealistic in isolation (see Section 5.4.7)

5.5.5 The Combination of Rainfall and Irrigation Inflow on Multi-terrace Systems

As on a single terrace system, rainfall is shown to be the most important variable, particularly when combined with increased irrigation inflow. The importance of this in multi-terrace systems is emphasised by referring to Table 5.6, which detailed applications where irrigation inflow to the single terrace system was varied. In Application T1-IR100-Eq irrigation inflow was increased to 100 l/min to illustrate the likely upper range of irrigation inflow. But 100 l/min is of comparable magnitude to inflow received by the lower terraces by the end of the storm when the standard storm was applied in Application T4-Benchmark. Application T1-IR100-Eq resulted in the single terrace establishing an equilibrium position with twice as much water, 5850 litres, than for the equilibrium position of the single terrace Benchmark Test with irrigation input of 10 l/min. Thus, when the Standard Storm is applied to the multi-terrace system the lower terraces are simultaneously receiving rainfall input and water outflow from the higher terraces of similar magnitude to a substantial irrigation increase, forcing the system to a higher equilibrium position. Additionally, as was explained for the single terrace model applications, in the field rainfall generates extra irrigation inflow to the top terrace, which is also forcing the system to a higher equilibrium position.

The combination of these three inter-related reactions to rainfall represents the most important process acting on multi-terrace systems, the cumulative reinforcement of rainwater volume as it travels through the khet system. This provides model confirmation of the cause of the failure (overflow) of the lower terraces of systems that have too many ‘drops’ and isolates the drivers of that process in the field. The importance of this process becomes more evident when longer terrace systems are modelled below and in Chapter 8. Again, it illustrates the importance of maintaining a water balance in khet systems.

5.6 Model Applications with a System of Twenty Five Linear Terraces

Using this number of linked terraces takes the model closer to conditions in the field, where 10 to 30 ‘drops’ is the usual size of khet terrace subsystems. However, when applying the model the problem of water balance soon became apparent, firstly in that it was not possible to provide an equilibrium position from which the magnitude of change would be measured for the terrace system at the rates applied in previous tests. Process rates applied were 10 l/min for irrigation inflow and 5 ml/m^2/min for both evapotranspiration and seepage, reasonable field values. On a 100 m^2 terrace, 5 ml/m^2/min equates to 500 ml/min for each of evapotranspiration and seepage. If irrigation is adding 10 l/min to the system but each terrace is losing 1 l/min to these processes, irrigation will not go beyond terrace number 10 and the terraces below will drain.

Irrigation was set to 50 l/min and an equilibrium position was attained at this value. 50 l/min is within the range of measurements taken in the field but represents a high value for constant irrigation, though not so during storms. It is necessary for the validity of this exercise to have constant values for variables not being tested but in reality irrigation would vary from zero to possibly very high values, depending on availability of water (which may be subject to time limited sharing agreements with neighbours). It is likely that ponding is maintained in subsystems during the longest inter-storm periods by the farmer turning irrigation on and off or varying the rate. This would not be onerous as it would only be performed perhaps once per day. However, from a modelling perspective during analysis of sensitivity it would not provide a true test and a constant rate is applied in the model applications.

Further problems maintaining water balance became evident when storms were applied to the system. Model Application T25-Eq established stability in the system and Model Application T25-Benchmark illustrates the reaction of the system to the standard storm, which was excessive compared to field observations. These are summarised in tables 5.13 and 5.14. These data show that all the terraces from T5 downwards experience peak increases of slightly more than 6000 litres. However, a more complete picture is obtained from the hydrographs for the terraces in Figure 5.9, which shows that the terraces from T5 onwards achieve this peak but terraces further down the system progressively retain high volume for considerable time after the end of the storm. Indeed, peak volume is only attained in T17, T21 and T25 43 minutes, 117 minutes and 313 minutes, respectively, after the end of the storm. This is because there is sufficient water trapped in the higher terraces of the system to maintain and even increase supply to the lower terraces, even after rain has stopped. However, once the input from rainfall ceases the hydrograph, though still rising, becomes shallow. The plateau at the top of the hydrograph remains for each terrace until sufficient water has drained from the system above to allow inflow to fall. This contributes to the protracted draining times and in this application it is 1171 minutes (almost 20 hours) before the whole system regains its equilibrium position.

Table 5.13 The Equilibrium Position for a 25 linear terraced system

Terrace	Volume (l)	Depth (mm)	Outflow (l/min)	Outflow ht (mm)
1	4350	44	49000	19
5	4250	43	45000	18
9	4150	41	41000	16
13	3950	40	37000	15
17	3850	39	33000	14
21	3650	37	29000	12
25	3550	36	25000	11

Table 5.14 Applying the Standard Storm to a 25 Terrace System

Terrace	Volume Peak / Increase (l)	Depth Peak / Increase (mm)	Outflow Peak / Increase (l/min)	Peak Outflow ht. (mm)	Time to Stability (mins)
1	6937 / 2587	69 / 25	138/ 87	44	108
5	10446 /6218	104 / 62	279/ 240	78	306
9	10460 /6318	104 / 63	280 / 230	77	463
13	10346 /6301	103 / 63	275 / 230	76	608
17	10235/ 6303	102 / 63	270 / 229	75	824
21	10126/ 6403	101 / 64	266 / 229	74	953
25	10019 /6403	100 / 64	261 / 229	73	1171

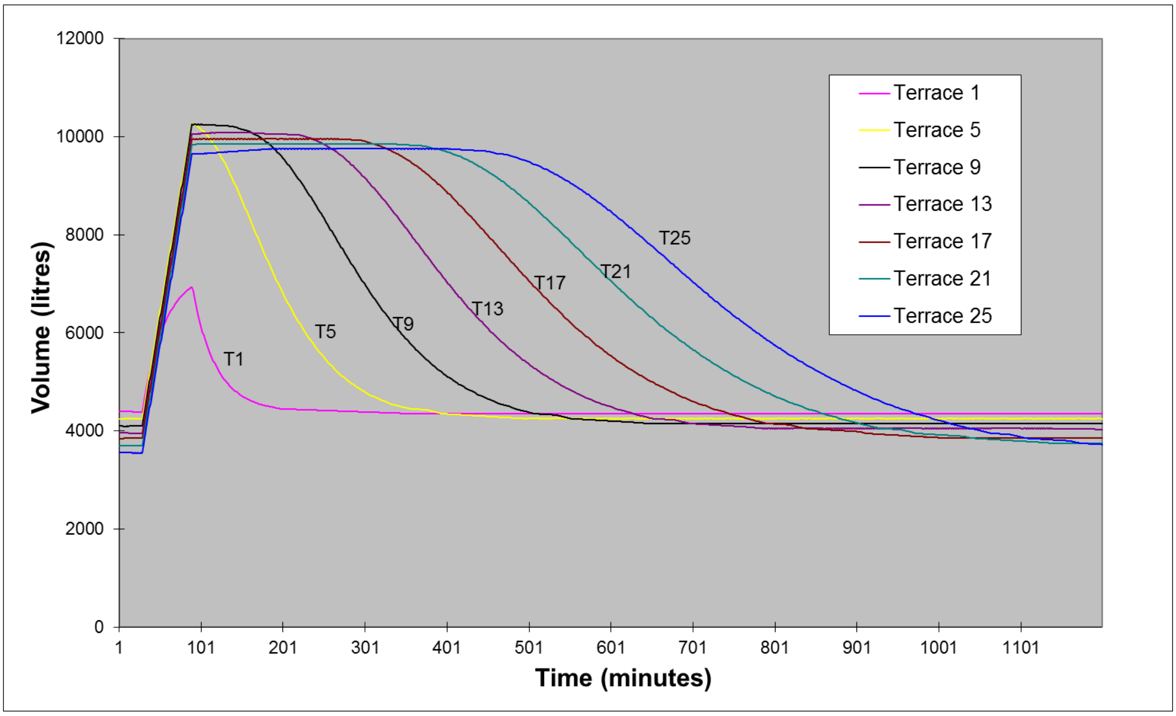


Figure 5.9 Water Volume in the 25 Terrace System after application of the Standard Storm

Two further tests were conducted on this terrace system for this initial stage of experimentation (many more were conducted for further experimentation reported in Chapter 8). The standard storm, which has a constant rainfall intensity of 60 mm/hr and duration of 1 hour, represented a modest monsoon storm of regular frequency (HMG Nepal 1997) and was selected for that reason. A heavier storm was then replicated, using the same process rates and terrace conditions but with the length of storm increased to two hours, still within the reasonable frequency range for monsoon storms. Finally, the model was applied with a more extreme storm of doubled rainfall intensity for the duration of 120 minutes, an intensity and magnitude that might occur 3 to 5 times each monsoon season in areas of Nepal that experience more intense monsoons (HMG Nepal, 1997; Mawdesley and Gardner, 1998).

If terrace reaction in this 25 terrace system to the standard storm appeared severe, replication of a storm of twice the magnitude of the standard storm, which still represented typical monsoon conditions, was extreme and severely out of line with field observations. Replication of the extreme monsoon storm produced results that were off the scale of what is conceivable. When the standard storm was applied, all terraces below terrace No. 5 reached depths of about 10cm and inter-terrace flow rates were greater than 250 l/min. The second application, doubling the duration, resulted in all terraces below terrace No. 5 attaining depths greater than 16 cms and inter-terrace flow rates well in excess of 500 l/min. The heavy storm of two hours duration at double the intensity of the standard storm resulted in totally unrealistic depths of almost 30 cms and equally unrealistic inter-terrace flows over 1200 l/min. Also of concern, is that for each of these applications the high depth recordings and unrealistic volumes of inter-terrace flow rates were maintained for over nine hours. Tables 5.15 and 5.16 summarise the results.

<u>Table 5.15 Applying the Standard Storm x 2 (rain 120 mins) to a 25 Terrace System</u>

Terrace	Peak Volume (l)	Peak Depth (mm)	Peak Outflow (l/min)	Peak Outflow ht. (mm)	Terrace Depth >10cms (mins)
1	5972	59	102	34	n/a
5	13738	137	475	112	113
9	16363	163	548	138	205
13	16619	166	560	141	294
17	16521	165	555	140	383
21	16420	164	550	139	471
25	16320	163	546	138	559

Table 5.16 Applying an Extreme Storm to a 25 Terrace System

Terrace	Peak Volume (l)	Peak Depth (mm)	Peak Outflow (l/min)	Peak Outflow ht. (mm)	Terrace Depth >10cms (mins)
1	8580	85	202	60	n/a
5	23022	230	880	205	185
9	28561	285	1175	260	287
13	29360	293	1218	268	379
17	29295	292	1215	267	473
21	29200	292	1210	267	566
25	29107	291	1205	266	659

The magnitude of these results can be compared to field measurements where terrace depths greater than 10cm during storms were possible but not often encountered. Inter-terrace flow rates of 500 l/min were never recorded. Sustained high depth recordings and inter-terrace flow were also not seen and, indeed, brought the danger of damage to the fabric of the terrace system. (In one field experiment V-shaped weirs had been deployed and caused severe backing up of water as they constricted flow in a modest storm. This resulted in the terrace bund collapsing, serious damage to terrace and crop by the resultant water release and obvious abandonment of the experiment).

Clearly, a terrace system consisting of 25 drops but with only one outlet per terrace (of the typical size being deployed) did not reflect reality and was, indeed, unworkable. The terrace system needed redesigning with terrace area / outflow number ratios adjusted to attain the required water balance to make the system operable. This is tested and the results reported in Chapter 8. The difficulty in finding a workable system illustrated the fine margins in this feature of terrace systems and again illustrated the control that the need to achieve water balance exerted on this aspect of terrace design.

Table 5.17a Ranking by Volume Increase - including multi-terrace applications

Rank	Previous Rank	Reference	Application	Volume Increase	% of Benchmark Test
1		T25-Rain120 (bottom terrace)	Increase rainfall intensity to 120 mm/hr - 25 terraces	12465	442
2		T25-Dur120 (bottom terrace)	Increase Rainfall duration to 120 mins - 25 terraces	12304	436
3		T4-Rain120 (bottom terrace)	Increase rainfall intensity to 120 mm/hr - 4 terraces	11555	410
4	1	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	6427	228
5		T25-Standard (bottom terrace)	Standard Test (25 terraces)	6203	220
8		T4-Standard (bottom terrace)	Standard Test (4 terraces)	5883	209
9		T4-ESR0 (bottom terrace)	Standard Storm - Evap, Seepage, Ret. flow = 0 - 4 terraces	5859	208
11	2	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	5269	187
13	3	T1-Rain150d24	Rain 150 mm/hr - Duration = 24 mins	4378	155
14	4	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	4067	144
15	5	T1-Rain120d30	Rain 120 mm/hr - Duration = 30 mins	4024	143
16	6	T1-Narrow	Narrow Outflow, standard storm	3873	137
17	7	T1-Rain90d40	Rain 90 mm/hr - Duration = 40 mins	3532	125
18	8	T1-Flow75	Set Flow coefficient to 75%, Standard storm	3371	119
19	9	T1-Rinfinity	Continuous rain, new stability achieved	3201	113
20	10	T1-Vweir	V-shaped Weir, standard storm	3174	113
21	11	T1-Flow90	Set Flow coefficient to 90%, Standard storm	3051	108
22		T4-Rain30 (bottom terrace)	Decrease rainfall intensity to 30 mm/hr - 4 terraces	2967	105
23	12	T1-IR0	Canal inflow closed, Qin zero - Standard storm	2931	104
24	13	T1-IR4	Reduce Qin to 4ml/min - Standard storm	2918	103
25	14	T1-IR6	Reduce Qin to 6ml/min - Standard storm	2901	103
26	15	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	2872	102

Rank	Previous Rank	Reference	Application	Volume Increase	% of Benchmark Test
27	16	T1-IR8	Reduce Qin to 8ml/min - Standard storm	2853	101
28	17	T1-Clear50	Change weir clearance, Standard Storm	2821	100
29	18	T1-Benchmark	Benchmark Test	2821	100
30	19	T1-IR15	Increase Qin to 15ml/min - Standard storm	2770	98
31	20	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	2756	98
32	21	T1-IR20	Increase Qin to 20ml/min - Standard storm	2725	97
33	22	T1-IR25	Increase Qin to 25ml/min - Standard storm	2672	95
34	23	T1-IR30	Increase Qin to 30ml/min - Standard storm	2623	93
35	24	T1-CP125	Set Change Parameter to 125%, Standard storm	2618	93
36	25	T1-IR100	Increase Qin to 100ml/min - Standard storm	2418	86
37	26	T1-CP110	Set Change Parameter to 110%, Standard storm	2375	84
38	27	T1-Seep333	Evap = 5, Seepage = 333, Ret.flow = 0	1784	63
39	28	T1-Wide	Inc. Outflow, standard storm	1764	63
40	29	T1-Rain30d120	Rain 30 mm/hr - Duration = 120 mins	1700	60
41	30	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	1485	53

Table 5.17b Ranking by Time to Stability - including multi-terrace systems

Rank	Previous Rank	Reference	Application	Stability time	% of benchmark Test
1		T25-Rain120(bottom terrace)	Increase rainfall intensity to 120 mm/hr - 25 terraces	1201	917
2		T25-Dur120 (bottom terrace)	Increase Rainfall duration to 120 mins - 25 terraces	1181	902
3		T25-Standard (bottom terrace)	Standard Test (25 terraces)	1171	894
7		T4-Rain120 (bottom terrace)	Increase rainfall intensity to 120 mm/hr - 4 terraces	337	257
8		T4-ESR0 (bottom terrace	Standard Storm - Evap, Seepage, Ret. flow = 0 - 4 terraces	327	250
9		T4-Standard (bottom terrace)	Standard Test (4 terraces)	315	240
10		T4-Rain30 (bottom terrace)	Decrease rainfall intensity to 30 mm/hr - 4 terraces	288	220
11	1	T1-Narrow	Narrow Outflow, standard storm	234	179
12	2	T1-Vweir	V-shaped Weir, standard storm	210	160
14	3	T1-Flow75	Set Flow coefficient to 75%, Standard storm	170	130
15	4	T1-IR0	Canal inflow closed, Qin zero - Standard storm	167	127
16	5	T1-Flow90	Set Flow coefficient to 90%, Standard storm	165	126
17	6	T1-Rinfinity	Continuous rain, new stability achieved	161	123
18	7	T1-IR4	Reduce Qin to 4ml/min - Standard storm	161	123
19	8	T1-Rain150	Increase rainfall intensity - to 150 mm/hr	156	119
20	9	T1-Evap20	Evap = 20, Seepage = 5, R/fl=0, Standard storm	153	117
21	10	T1-ESR0	Standard Storm - Evap, Seepage, Ret. flow = 0	152	116
22	11	T1-IR6	Reduce Qin to 6ml/min - Standard storm	151	115
23	12	T1-Rain120	Increase rainfall intensity - to 120 mm/hr	150	115

Rank	Previous Rank	Reference	Application	Stability time	% of benchmark Test
24	13	T1-Rain150d24	Rain 150 mm/hr - Duration = 24 mins	145	111
25	14	T1-Rain90	Increase rainfall intensity - to 90 mm/hr	143	109
26	15	T1-Rain120d30	Rain 120 mm/hr - Duration = 30 mins	142	108
27	16	T1-IR8	Reduce Qin to 8ml/min - Standard storm	140	107
28	17	T1-IR100	Increase Qin to 100ml/min - Standard storm	139	106
29	18	T1-Rain90d40	Rain 90 mm/hr - Duration = 40 mins	137	105
30	19	T1-Clear50	Change weir clearance, Standard Storm	131	100
31	20	T1-Benchmark	Benchmark Test	131	100
32	21	T1-IR15	Increase Qin to 15ml/min - Standard storm	125	95
33	22	T1-IR20	Increase Qin to 20ml/min - Standard storm	117	89
34	23	T1-Rain30d120	Rain 30 mm/hr - Duration = 120 mins	114	87
35	24	T1-Rain30	Decrease rainfall intensity -to 30 mm/hr	109	83
36	25	T1-IR25	Increase Qin to 25ml/min - Standard storm	108	82
37	26	T1-IR30	Increase Qin to 30ml/min - Standard storm	98	75
38	27	T1-Wide	Inc. Outflow, standard storm	61	47

5.7 Summary of Sensitivity Analysis

Section 5.4.8 summarised the results of sensitivity analysis on a single terrace system, showing that the most important variable acting on the khet system is rainfall intensity, particularly when coupled with irrigation inflow, of which it is the main component during a storm. Each terrace in multi-terrace khet systems has the same sensitivity as when considered in isolation. The importance of sensitivity analysis on multi-terrace systems was to highlight the complexities such systems introduce as processes are propagated down the system.

As described in Section 5.5 the effect of water input is intensified in lower terraces in the khet system. Tables 5.17a and 5.17b detail the magnitude of this, comparing the reaction of the bottom terrace of multi-terrace systems (representing the cumulative effect on such systems) to the rankings for peak volume and time to stability in single terrace systems.

In rankings for both peak volume and time to stability the magnitude of change is clearly greater on the bottom terrace of a 25 terrace system; and the magnitude of change on the bottom terrace of a 4 terrace system is clearly greater than that for a single terrace. Furthermore, in every application of a multi-terrace system both the peak volume attained and the time to regain equilibrium of the bottom terrace was at least twice the magnitude compared with the same test on a single terrace system. It should be noted that increased irrigation caused by rainfall, which was shown to intensify the magnitude of change on a single terrace system, was not included in the multi-terrace tests.

Section 5.4.6 discusses the interaction between rainfall and irrigation flow and section 5.5.5 discusses the cumulative reaction of multi-terrace systems to rainfall. These provide valuable insights and show how these processes act in combination and suggested that the reaction of terrace systems to rainfall is intensified both by increase in irrigation inflow and, particularly in the lower reaches of the system, cumulative increase in terrace outflow. The combination of these processes is the model depiction of the probable explanation for the failure (overflow) of large terrace systems in many storms in the field and represents the most important process acting on multi-terrace systems.

The sensitivity analysis also suggests that in single terrace systems (analogous to the top terrace of the khet system) the time the system takes to regain stability is relatively quick, often only a few hours. However, the full khet systems tested in this exercise took considerably longer to recover their start position, even from quite modest storm events. Further work in this area of research on more realistic terrace configurations is reported in Chapter 8 but initial conclusions suggested that the antecedent position of the terrace system may be important; if there is still water in the system from the previous storm reaction will be more severe.

The results of the sensitivity analysis support the goal of predicting khet behaviour from a small number of measured variables. Measurement of rainfall and irrigation inflow are critical to understanding the behaviour of terrace systems and are of considerably greater magnitude than evapotranspiration, seepage and return flow.

Finally, and most importantly, sensitivity analysis has highlighted the narrow range of variables within which the system operates and the importance of the need to maintain water balance. This was starkly illustrated when modelling the 25 terrace system at seemingly reasonable process rates and with normal terrace characteristics (as applied elsewhere in the sensitivity experiment) when the system was rendered inoperable.

5.8 Implications of the Need to Maintain Water Balance

A constant theme throughout this chapter has been consideration of the need to keep a water balance in the system, which is fundamental to understanding the way the system functions and thus to modelling it. ***Rainfall and rainfall reinforcement of irrigation inflow have been shown to be the processes that drive the system but overriding this, from a modelling point of view, is the need to maintain a water***

balance throughout the system. If the model is to be a viable representation of reality, this requirement represents the most important control. A model that seeks to replicate khet hillside processes has to recognise and take into account this circumstance.

The need to maintain water balance is reflected in the pragmatic design and construction of khet systems on Nepali hillsides. Khet system design is not formally prescribed but rather has developed from farmer trial and error. For a khet system to function properly there almost always has to be an irrigation source at the very top of a system. To build a khet system the farmer will first identify or construct such a source of water. During the monsoon, when water is plentiful, the farmer will then break into the water source above the slope on which he or she is building the system so that water flows freely down the slope. He or she will then start digging out the terraces, from the top down, whilst water is flowing through them. When the first terrace is sufficiently flat to ensure ponding and the maximum size possible for the slope and shape of the hill, the farmer simply starts on the next terrace down by breaking the bund (lip) of the first terrace at the optimum point, and repeating the process. In this way, the terrace system is constructed from the top down and moulded to the morphology of the hillslope. Terraces on wider, shallower hillslopes may naturally cross ownership boundaries and several farmers may be involved in their construction but when the terraces are completed boundaries will be replaced to prevent flow of water from one farm to another, thus creating the characteristic khet subsystems seen throughout the Middle Hills and previously described in Section 3.2.

It has been stated that there is little to be gained from modelling storms of unrealistic intensity or magnitude ten times greater than ever recorded; or of applying irrigation rates so high that, if occurring in the field, the khet fields would be destroyed. Equally unrealistic are situations that render the system inoperable because there would be too little water, so as to quickly drain the higher terrace(s) so that no water flows through the system and the lower terraces are dry. This is not to suggest that process rates that result in there being too much water in the system don’t occur in the field. These situations arise and overtopping ensues. Situations also occur when terraces drain during long inter-storm periods when irrigation, for whatever reason, is not available. However, when applying the model to speculate on the possible reaction of khet hillslopes to different monsoon conditions, there is nothing to be gained from modelling process rates that ***directly*** result in excessive overflow or draining as they will never reflect reality.

Similarly, as discussed in section 5.4.7, it is equally uninformative to model situations where terrace characteristics, such as area and outflow size and number, are changed in isolation so that it directly results in excessive overflow or draining as this also will never reflect reality. In reality, through a process of trial and error during the building and operation of the terraces, the farmer would set outflow size and number proportionate to the terrace size to keep the system in balance.

This control of terrace design, where terraces have to be structured to allow continuous flow from top to bottom, has to be reflected in the modelling process and is a prime consideration when deciding which situations should be modelled. Experiments described above on the 25 terrace system showed that the terrace system was not viable when designed with only one outflow per terrace. In Chapter 8, experiments conducted on terrace systems with different configurations of terrace outflows are explained, with the purpose of finding a design for a workable system on which to conduct further modelling.

Designing a workable system also had important implications for the approach to the remaining research, which aims to speculate as to the reaction of khet systems when monsoon storms in different situations and over longer time frames are applied to the model. Such research has to be designed to reflect realistic situations and, after the calibration and validation of the model are described in Chapters 6 and 7, this is also considered in depth in Chapter 8.

Chapter 6 - KhetFlow Model Calibration

6.1 – Introduction

This chapter describes the calibration of the KhetFlow model, using field data collected in Nepal. The most important function of this section is to show that the model works, that is, it can be used to predict the surface hydrological response of khet systems to storms with reasonable accuracy.

Work undertaken for the perceptual model, conceptual model and the sensitivity analysis described in Chapters 2 and 5 respectively has shown that during monsoon storms the khet system is most sensitive to rainfall intensity and the interaction of rainfall and irrigation input and that there is an important control on the system as it only works within a narrow range of variables. Rainfall and irrigation input can be quantified in the field whereas the less important parameters of evapotranspiration, seepage and return flow cannot be measured for each storm and have to be estimated. A further purpose of this chapter is to determine constant values for these less important parameters, within the context of the model.

It is important to be able to establish appropriate values for evapotranspiration, seepage and return flow, even though they are not as crucial as rainfall and irrigation input. These parameters are more difficult to measure in the field and if the model is to be easily transferable it needs to be shown that they can be accurately estimated at realistic rates in line with field measurements.

The model was calibrated for a khet system of 4 linear terraces, designated Khet HA, using data from 6 storm events of varied intensity and character monitored in a second field season. The calibration was performed by inputting the terrace parameters into the model and running the model using the rainfall and irrigation variables measured during each of the six storms. The parameters to be estimated were then amended to establish the best fit to field data. These values were then tested on other terrace systems during the validation process reported in Chapter 7.

This chapter describes the terraces and the events used for the calibration, explains the calibration procedure and reviews the results.

6.2. Terraces

The Khet HA terraces monitored were roughly square with water flow between a single inlet and single outlet, each positioned centrally in the bund. The terraces were numbered sequentially starting at the top, terrace areas were:

HA1 - 67.14 m^2
HA2 - 26.37 m^2
HA3 - 25.34 m^2
HA4 - 24.13 m^2

6.3. Events

Six discrete events, each different in character, were used to calibrate the Khetflow model against field data collected on Khet HA. Five of the events were storms and one the release of irrigation water into dry terraces. The magnitude of the storm events varied from 4.8mm to 34.4mm and the duration from 17 minutes to 6 hours 36 minutes. Monitoring periods for the events, and thus model application durations, varied from just under 5 hours to 11 hours.

The events were monitored from the start of rainfall or shortly beforehand, through the peak of the event and during the falling limb until such time that the system was draining at a constant rate and had reverted to similar levels as the start conditions, or was at or close to a new equilibrium. However, it should be noted that the system is one of dynamic equilibrium and the normal condition is that it is slowly altering towards a changed equilibrium position. At the start of the event the system may have still been changing to a new equilibrium and at the end of the event, particularly when irrigation levels had been changed by rainfall, this was also likely to be the case.

The six storms represent a wide range of conditions on which to base the calibration procedure. Table 6.1 summarises the event characteristics and Figure 6.1 illustrates and compares the intensity of each storm.

Table 6.1 - Storm Characteristics

	Rainfall		Max	Mean	Irrigation			Model	
Event	Duration	Magnitude	Intensity	Intensity	Start	Peak	End	Duration	
	mins	mm	mm/hour	mm/hour	l/min	l/min	l/min	mins	
	**1		**2	**3				**4	
Jul-11	208	17	24	7.6	0	22	1	256	**5
Jul-13	0	0	0	0	50	50	50	340	**6
Jul-16	265	10	11.1	3.7	10	56	36	520	
Jul-17	395	34.4	44.4	10.1	0	5	0	660	**7
Jul-30	17	4.8	48	16.9	22	26	19	556	
Jul-31	175	11.4	12	3.9	20	36	22	556	

Notes:

**1 Start of first rain to end of last rain - can include dry periods
**2 Max 15 minute period
**3 Start to finish of main storm
**4 Model duration is the same as duration of monitoring
**5 Unmonitored inflow to bottom terrace so system modelled as a 3 terrace system
**6 No rainfall, controlled release of irrigation water to previously drained terraces
**7 Possible unmonitored inflow to bottom terrace so system modelled as a 3 terrace system
- same conclusions drawn in each case

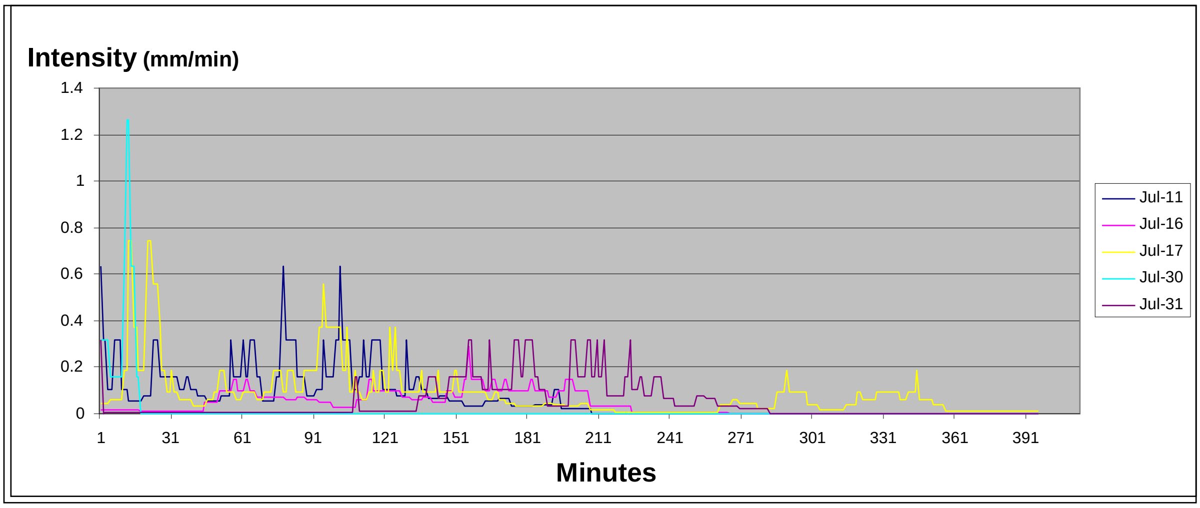


Figure 6.1 Comparison of Intensities of the Calibration Events

6.4. Calibration Procedure

The basis of the calibration procedure was to compare the field measurements for each of the above events with values predicted by the KhetFlow Model when using the same data as measured in the field for rainfall and irrigation inflow. The parameters to be calibrated were varied between applications, within an appropriate range determined by field measurements and using knowledge gained from the development of the perceptual and conceptual models described in Chapter 2 and the sensitivity analysis reported Chapter 5. Using the techniques described below, this procedure was followed to find the best fit of the model to field data for each of the storms simulated.

The field measurement techniques are described in Chapter 4. For each event this provided the following data:

- Rainfall intensity, per minute (mm/min);
- Irrigation inflow, monitored periodically during each event, converted to ml/min values by interpolation;
- Water depth (mm), volume (ml) and outflow (ml/min) from each terrace, monitored periodically during each event; volume calculated by multiplying depth by area, outflow converted to ml/min values by interpolation where necessary;
- Estimates of prevailing evapotranspiration, seepage and return flow rates from which losses/gains of water from the terrace per minute could be calculated (ml/min/m^2).

Data with a resolution of one minute for each of the input variables for each terrace, together with measurements at the same resolution for terrace depth, water volume and inter-terrace flow, allowed a hydrograph for each terrace to be constructed for each event (reported as the field values in the various figures that accompany this chapter). The model was then used to predict each event to the same resolution from the given input values and the model prediction was compared to the field measurements, least squares scores calculated and terrace hydrographs generated by the methods described in Section 4.8.

To assess how each model application matched field data, two methods were used. The most important was a mathematical calculation based on a least squares method. However, as is explained below, it is also necessary to visually compare the respective graphs to confirm that the least squares assessment was reasonable.

Least squares values were obtained for each terrace by comparing field and model terrace depths for each minute, squaring the difference, summing the total of differences for the duration of the event, and then dividing by the number of minutes to provide a figure of ‘least squares per minute’ for each terrace. Finally, the least squares figures for each terrace were added together to give a total value for the whole system for a particular application (see Section 4.8). This also illustrates that the model is predicting as a continuous series, the measurements are periodic. As explained in Section 4.8, least squares values are presented without dimensions.

Calculation of a ‘least squares per minute’ figure was undertaken to allow a basis for comparison between events of different duration but also from a practical point of view to display the results in a presentable manner. However, it is recognised that the different character of each event renders this problematic. Differences during a long and stable ‘lead-in’ before rainfall starts or during a long falling limb when the system was in equilibrium (for example, July 30th and 31st applications) will bias least squares values and appear to make particular model applications seem less (or more) accurate when a visual comparison, concentrating on the actual storm period, might indicate that the model provided more (or less) accurate predictions of the main characteristics of the hydrograph than the least squares ‘score’ indicated.

Terrace water depth figures were used to calculate least squares values (rather than figures for the actual water volume) so that the figure for the terrace system as a whole would not be biased towards the accuracy of the prediction for the largest terrace.

The results should be considered in the context of acceptable field data error margins in the circumstances prevailing when monitoring took place. The hydrographs produced are of terrace volume throughout the event. Volume was calculated by measuring depth in mm and multiplying by terrace area, the depth reading either being taken from a calibrated metal pole fixed in the terrace floor or by measurement of the depth of water flowing through the outflow weirs (plus the clearance of the weir from the terrace floor). Measurements often had to be taken at night, by torchlight and/or whilst it was raining and/or whilst the researcher was perched on the muddy, slippery 15-30cm wide divide between the terraces. In these conditions a margin of error in the field readings of 5mm would be well within acceptable limits.

Figure 6.2 plots a 5mm margin as error bars (black lines) aligned to the field measurements and, as there is a direct relationship between depth and volume, shows how small changes in depth measurements (right hand axis) translate to differences in volume (left hand axis), and vice versa. The figure illustrates that the best fit for the July 16th event, model application July16-107 falls completely within the 5mm field measurement error bars.

This level of accuracy is repeated for the best fit application for each of the events and shows that the model falls well within reasonable field error limits. This closeness of fit should be taken into consideration when comparing all graphs of field values and model predictions.

Similarly, when considering the figures for least squares some leeway for measurement error should be accepted. The least squares figure is calculated for each minute and then a mean figure for the duration of the model event calculated. A least squares mean of 25 or less for any terrace could be considered very accurate as this represents a mean divergence of 5mm or less, less than field error margins, between the two sets of data. Least squares scores of 100 or lower per terrace, representing predictions within a centimetre, can also be considered accurate.

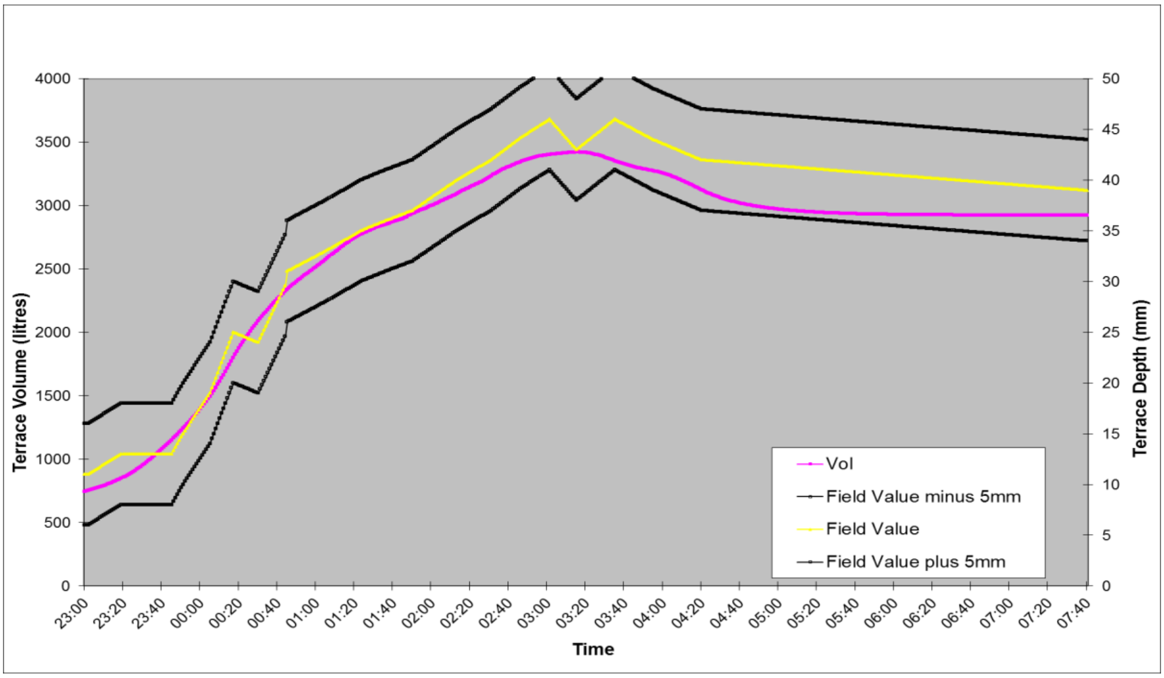


Figure 6.2 Field Error Margins – Application July 16-107

Conversely, low least squares scores are sometimes achieved when the model prediction is consistently within the margin of error but when simple observation of the relevant hyrograph shows that the model prediction is erratic and may include obvious severe errors, for instance frequently deviating above and below the field values. This might include examples when there were visible differences in the prediction of fundamental points in the event, such as the time of the onset of rain or peak volume and examples where the model prediction is a totally different shape to the field data but errors cancel each other out so that overall it remains close to or within the margin of measurement error.

It is thus reasonable to review the model predictions/comparisons with field data both visually and mathematically, even though the former may introduce subjectivity.

6.5. Calibration Input Variables and Parameters

The input variables and parameters in the Khetflow Model are:

Initial Store level (l)
Rainfall (mm/min)
Irrigation Inflow (ml/min)
Evapotranspiration (ml/min/m^2)
Seepage (ml/min/m^2)
Return Flow (ml/min/m^2)

From the point of view of the model these variables can be separated into two categories:

- Rainfall and irrigation inflow are the ‘drivers’ of the system. These have been determined by accurate field measurement.

- Evapotranspiration, seepage and return flow are variable, depending on location and circumstance, particularly in the context of rural Nepal. The system is much less sensitive to change in these variables and it has been shown in Chapter 5 that they have to be taken to unworkable extremes before they exert a strong influence. Field measurements have determined a reasonable range for each of these, as reported in Chapter 4.

The operation of the model and the calibration exercise can be simplified without sacrificing accuracy by considering evapotranspiration, seepage and return flow as acting in conjunction with one another. Because the rates of evapotranspiration, seepage and return flow are shown to be relatively unimportant, in the KhetFlow Model they are combined as a net figure and treated (in the model) as a function of surface area. Evaporation is related to the water/air surface interface and seepage is related to the water/soil interface, in this system these two surface areas are virtually of identical size because the shallow water depth and vertical sides of the ‘pond’. Return flow is indirectly related to area as a subset of seepage. As was explained in Section 5.4.7, it is not suggested that in the physical world area is the only component of these processes, only that at the scale required for this study this approach provided sufficient accuracy, particularly as gains from return flow mitigate losses from evapotranspiration and seepage.

Additionally, evapotranspiration has little sensitivity in this system even when conditions are such that it would be at a maximum. During the events monitored for this calibration it was usually raining, often during the night and there was no crop, so no transpiration. It is thus reasonable to assume field values for evapotranspiration would be unimportant at the scale being modelled. In some instances seepage values could be relatively high if there was an extensive macropore system in the khetland, as described in Chapter 4, but such high values were extremely unusual and quickly drained the system, changing the farming method. This variable was also shown by sensitivity analysis in Chapter 5 to be relatively unimportant in the context of the overall system when set at reasonable values. Return flow was shown to be almost totally a function of, and thus from the point of view of the model a percentage of, seepage.

As such, particularly as they are relatively unimportant in the system, it is possible for the purpose of calibration of the model to effectively assign one value to all three for net loss (or, less likely, net gain) per unit area.

In Section 5.4.7 the model was tested to ensure that exactly the same results were obtained if these three variables were set individually or collectively, provided the net figure was the same, eg. evaporation 50 ml/m^2/min, seepage 200 ml/m^2/min, return flow 75% at 150 ml/m^2/min, net 100 ml/m^2/min; produced the same results as evaporation 10 ml/m^2/min, seepage 180 ml/m^2/min, return flow 50% at 90 ml/m^2/min, net 100 ml/m^2/min. This was the case and it is thus legitimate to combine these three variables in the model for calibration purposes.

This simplifies the calibration exercise as it means that, as rainfall and irrigation inflow are determined by field values, only one parameter needed calibration to compare field and model events. This is now referred to as net loss per m^2 from evapotranspiration, seepage and return flow which, as with its constituent parts, has to remain within a reasonable range for the system to function and is relatively unimportant compared to rainfall and irrigation. Provided the calibration exercise is successful, this simplification will greatly assist the goal of using the model as a tool of prediction as it reduces the number of input variables required.

6.6. Calibration Results

6.6.1 Calibration Results Format

The model was applied for each rainfall/irrigation event with all parameters constant whilst net loss was systematically varied until the optimum fit was determined. These model applications are referred to below as the calibration series of applications. The optimum fit for an event was considered to be that with the lowest least squares score for the total of the four terraces, with the important proviso that the corresponding graphs should be considered visually to confirm the validity of the least squares index. Table 6.2 – Khet HA Results Summary lists the conditions tested and the least squares score for the full system for each application modelled. The figures in bold show the best fit for each series.

Figure 6.3 illustrates graphically results for the July 16th event, plotting change in the least squares scores as net loss is amended. In the Calibration Series A the net loss figure varied between 5 and 300 ml/m^2/min, the latter, as explained in Sections 4.5 and 5.4.7, beyond reasonable high values for net loss. A U-shaped pattern can be seen. As net loss is systematically increased, the corresponding least squares score deceases until a net loss figure of 90 ml/m^2/min produces a corresponding least squares score of 93. When net loss is increased above 90 ml/m^2/min subsequent least squares scores increase. The optimum figure for net loss, for this event in the series, is thus 90 ml/m^2/min.

Table 6.2 Khetland HA - Results Summary

Model									
Application			Events/Least Squares Score						
Reference	Net Loss		11-jul (3)	13-jul	16-jul	17-jul	17-jul (3)	30-jul	31-jul
100	5		48	495	320	252	237	186	88
143	30					134	122		55
144	40		22			104	85		
104	50		**21**			**89**	57		38
101	60		24	299	132	112	**45**	64	37
105	70				112	137	85	51	31
145	75								**30**
106	80				98			43	31
107	90				**93**			**39**	
102	100		84	196	98	497	254	40	55
146	110				116				
108	125			153	155				
142	140			137					
140	150			132					
141	160			**131**					
147	170			136					
103	200			190	283			914	801
109	300			721					
No. of Applications			**5**	**10**	**9**	**7**	**7**	**7**	**9**
Total Model Applications			**54**						

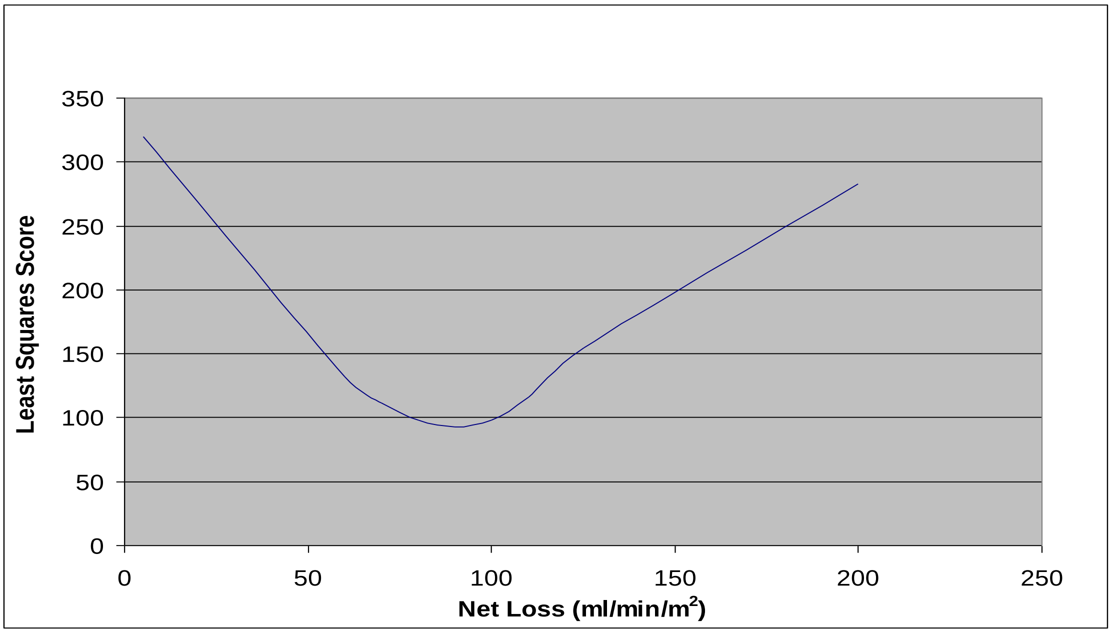


Figure 6.3 July 16th Event - Least Squares Score v. Net Loss

The U-shaped pattern is important because it indicates systematic results, the greater the deviation from the optimum net loss figure, the higher the least squares score, which alongside visual corroboration of the hydrographs, indicates accuracy. This systematic U-shaped pattern is seen, without exception, for all storm events within the

Calibration Series (and later the Validation Series) and such uniformity gives confidence in the results produced by the model.

6.6.2 Calibration Predictions

The least squares scores for the optimum fit for each event in the Calibration Series are shown in Table 6.3. For the optimum predictions the figure for net loss ranges from 50 to 90 ml/m^2/min, with the exception of the 160 ml/m^2/min recorded for the July 13 event. Respective least square scores ranged from 21 to 93, again with the exception of July 13, when the score was 131.

Table 6.3 Lowest Least Squares Score and Corresponding Net Loss value for each event in the Calibration Series

Event	Score	Net Loss (ml/m^2/min)
July 11(3)	21	50
July 13	131	160
July 16	93	90
July 17	89	50
July 17(3)	45	60
July 30	39	90
July 31	30	75

With the exception of the July 13th event, the modelling of all these events produces an accurate replication of the field data. Visual appraisal of the terrace hydrographs of the optimum fit for each event in Appendix A1 confirms consistency, especially when considered in the context of the margin for measurement error demonstrated in Figure 6.2. In particular, in almost all of the 24 hydrographs presented both the shape of the graphs and the timing of the major components reflect field values with considerable accuracy.

The range of net loss values for the optimum fit application for five of these model applications, from 50 to 90 ml/m^2/min, are slightly higher than was indicated by field measurements but not outside the narrow range required for successful khet terrace operation. It was explained in Chapter 4 that the field methodology was not expected to provide accurate measurements for these processes but to confirm that estimates used when modelling are realistic approximations of process rates. This is shown to be the case but further fieldwork is required to determine whether the slightly higher rates predicted by the model are accurate.

The model itself lends credence to the range of values for net loss estimated from field data. Whilst the circular argument of producing results from a model to prove that it works is not acceptable the results show that if the value for net loss is set much higher than 125 ml/m^2/min the model breaks down (depending on the situation being modelled). The model (and the field system) relies on the continuity equation and the system, because of the linear nature of the terraces, relies on there being sufficient water input to each terrace (especially in the lower terraces). It is a practical example of the research control that it is impossible to accommodate variables outside a certain range because if the system becomes out of balance and does not provide sufficient input to lower terraces, such figures cannot be considered credible. If the net loss figure in the model is set too high, the terraces quickly empty and the system breaks down because no water can flow. This is illustrated in Figure 6.4a, showing applications for the July 16th event when the net loss figure was set to 125 ml/m^2/min and, more extremely, in Figure 6.4b for the July 30th event when the net loss figure was set to 200 ml/m^2/min. In both cases the lowest terrace empties even during the storm when these unrealistic net loss figures are used.

To summarise the Calibration Series applications, five of the six field events recorded were accurately predicted when values for net loss are set within the 50 to 90 ml/m^2/min range indicated by field data. The exception, the event of July 13th, is discussed below.

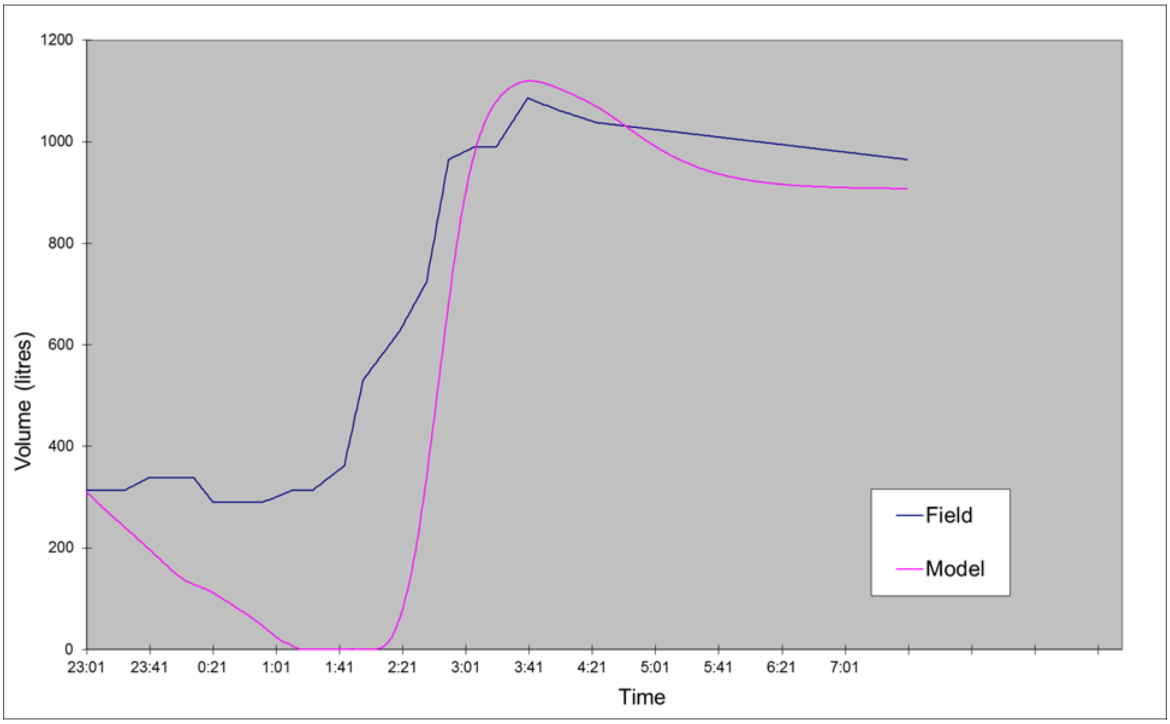


Figure 6.4a July 16-108 Terrace HA4 Water Volume

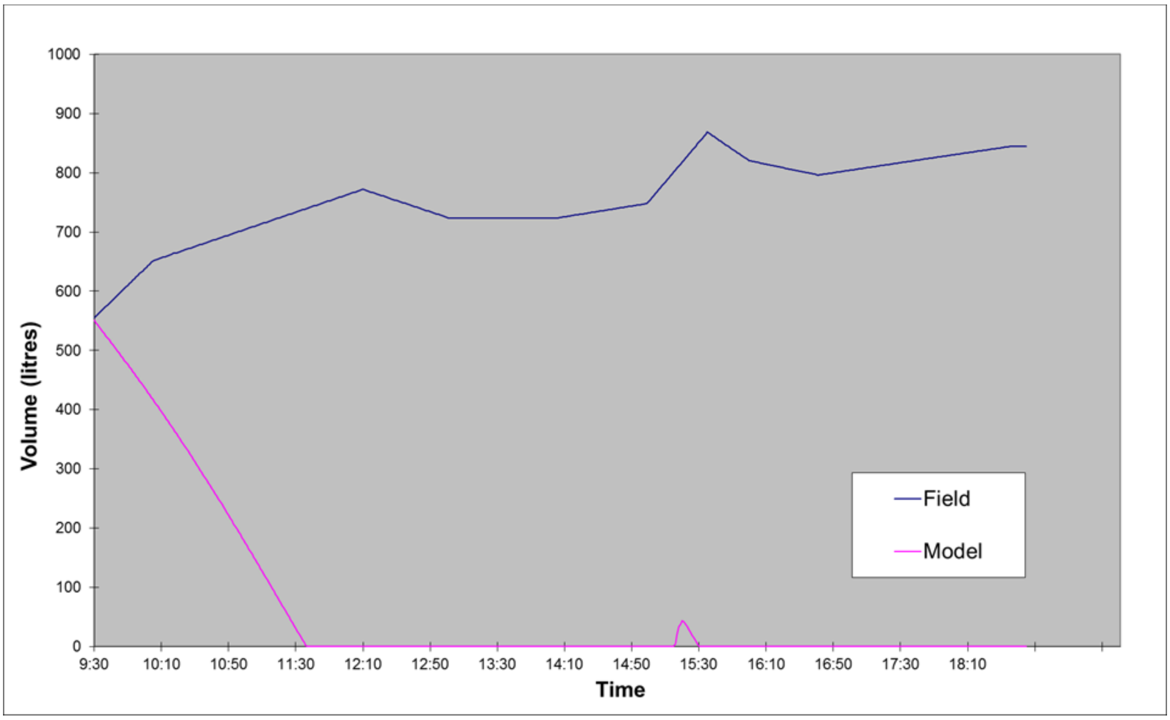


Figure 6.4b July 30-103 Terrace HA4 Water Volume

6.6.3 Calibration Predictions – Individual Events and Terraces

This section discusses the accuracy of model predictions for each on the Calibration Series events.

July 11th - The scores for this event are all very low, indeed, the lowest of all the Calibration Series. The optimum fit occurred when net loss was set to 50 ml/m^2/min and the least squares score totalled only 21 (thus only 7 for each terrace) at this rate of loss.

Individual Terraces – The magnitude of this event is well replicated in each terrace, as are the slopes of the rising and falling limbs, although the model prediction for the rising limb of HA3 is too flat. However, the timing of peak volume is consistently 20-30 minutes late, part of which possibly reflects that a field measurement was not taken at the precise moment peak volume occurred.

July 13th - This event was anomalous both in that all least squares scores were high and that the optimum fit of 131 was only attained when net loss was set very high at 160 ml/m^2/min. Even though this is only marginally higher than the 1cm per terrace error margin the prediction is not thought to well replicated the event because the net loss figure is higher than field measurements and sensitivity analysis suggest is viable. The least squares scores for applications of this event, high as they are, might be artificially low as only the rising limb of the event was monitored in the field and so only this section of the event could be modelled. The net loss figure had to be set unrealistically high to find the optimum fit. The likely differences between the field and model data that would result from this would be most noticeable during the falling limb, when this variable has more influence. The absence of the falling limb also means that there are fewer keys points in the hydrograph to replicate and this makes the fit less complex. This event is different to the others in that a storm is not being monitored, the system is fed by irrigation inflow only. It also started with dry terraces as opposed to the ponding at the start of other events and, although the model is designed to cater for this and there is no reason why this in itself should promote inaccuracy.

Individual Terraces – Whilst the least squares scores for the optimum fit are high, visually comparing the graphs for the optimum fit in each series of data shows that there is actually less difference than might be expected between the field and model data and that for each terrace the model provides a good replication of the shape of the field data hydrographs.

July 16th - Again both the optimum fit score and the figure for net loss for the optimum fit application were high but for this application, within acceptable range with the optimum fit least squares score being 93 (22.25 per terrace) and the net loss for the optimum application 90 ml/m^2/min. Of the Calibration Series events that provided reasonable predictions (ie. excluding July 11th), this was least well replicated event, though still acceptable.

Individual Terraces – The timing and magnitude of the major events in the field are well replicated but for the bottom two terraces the model tends to under then overshoot and the model predicts a loss of water from the bottom three terraces early in the application before rainfall starts that was not seen in the measured data. The slope of the falling limb for the final 3 ½ hours of the event is not well replicated but this may be because there was no field recording between 4.15am and 7.30am and field data were extrapolated between these points.

July 17th – For this event the Khet HA terraces were considered as both a three terrace and a four terrace system because there were fears that ungauged water infiltrated into the lowest terrace (see Section 4.6). The least squares scores for the optimum fit reduced by almost 50%, from 89 to 45, when only the top three terraces were included, though the net loss figure increased marginally from 50 to 60 ml/m^2/min.

Individual Terraces – For this event the timing of the major events is again well replicated but the shape of the model hydrograph when compared to the field data is less accurate. The reason for the decrease in least squares score when only three terraces are included can is evident as the suspected unmonitored influx of water into the lowest terrace can be clearly seen. At 89 the least squares score is relatively high but acceptable, a least squares score of 45 for the three terrace systems can be considered a good model prediction.

July 30th – A good replication of field values indicated by the least squares score of 39 (9.75 per terrace), and although net loss for the optimum application was a little high at 90 ml/m^2/min this is acceptable.

Individual Terraces – Again the timing of the major components of the field hydrograph is well replicated in the model application. For this event the storm only starts after 5 ½ hours and there are differences between the two graphs in the long 'lead-in' to this. However, during the lead-in period irrigation is constant and the system is in equilibrium, so the hydrograph should be smooth, as in the model application and the variances recorded in the field data. The variations in the field recordings are likely to be slight measurement errors.

July 31 – Again a good replication of field values. The least squares score for the optimum fit application of 30 represents 7.5 per terrace. Net loss for this optimum application was 75 ml/m^2/min, acceptable for the system.

Individual Terraces – Except for terrace HA4 the shape of the hydrograph for each terrace and the timing of the key events, particularly the peak volume, are well replicated. With HA4 the problem is the shape of the rising limb but this probably reflects field data error. There was a slight amount of rain in the first 15 minutes of this event but the main storm did not start until 2 hours had elapsed. This early rainfall is seen in both the field and model data for terraces HA1, HA2 and HA3, though the timing is slightly awry, but not in the field data for terrace HA4.

6.7 Summary of Calibration Applications

In this chapter the predictions of the Khetflow model have been compared to field data to test its accuracy and calibrate the parameters. The overall accuracy of the model predictions was very encouraging, many of the model predictions being within +/- 5mm of the field data and it can be concluded that the Khetflow model reflects the field data for the rainfall events monitored with acceptable accuracy.

The results show that net loss from evaporation, seepage and return flow can be estimated and calibrated within the bounds of reasonable field values. Five events provided acceptable replications of field values (excluding the event of 13th July) and the mean net loss figure for those events, 73 ml/m^2/min, was taken forward for the validation exercise.

The systematic nature of the results, which produced a U-shaped graph of least squares scores for each event within each series of data, gave confidence in the procedure and enhanced the validity of the model. The net loss values for the model applications providing the optimum fit are slightly higher than was indicated by field measurements and further fieldwork is required to determine whether the rates predicted by the model are accurate representations for the region.

Chapter 7 - KhetFlow Model Validation

7.1 Introduction

This chapter describes the validation of the KhetFlow model prior to its utilisation to predict and analyse hillslope response in Chapter 8. The validation exercise tested the integrity of the model against new field circumstances and completed the model development cycle. The predictive applications described in the following chapter then show that it will be of use when evaluating response to monsoon storms at the hillslope and catchment scale.

The Sensitivity Analysis (Chapter 5) showed that the khet system is most responsive to rainfall intensity and the interaction of rainfall and irrigation input and that the system as a whole will only function when many environmental variables are set within a narrow range. This is an important control because it shows that the acceptable range of process rates outside which the system breaks down is very constricted. The calibration exercise (Chapter 6) consisted of comparisons of a series of model predictions against field data for a small khet system of 4 terraces, assigning different values to parameters in order to find the most accurate fit. Calibration in this manner suggested that environmental variables can be estimated within reasonable limits and with sufficient resolution for the model to be valid. In this chapter the values determined by calibration are applied to events monitored on different khet systems to test the robustness of the model. After the model is shown as retaining its integrity during validation it is deployed in Chapter 8 to evaluate the response of khet hillslopes to monsoon storms in different situations.

7.2 Validation Overview

Four validation applications were performed using two separate linear khet systems. Each was larger than the terrace system used for calibration in Chapter 6, having 7 linear terraces and 18 linear terraces respectively, compared to the 4 terrace system previously reported. Tests on larger terrace systems, particularly the 18 terrace system, are important as these are closer representations of typical terrace sub-systems in the Middle Hills, as it is normal that the hillslope is divided into sub-sets of terraces consisting of usually 10 to 30 terrace ‘drops’ between each irrigation canal or stream. Validation of the model against typical monsoon events on larger khet systems will help to illustrate that the model will be a useful tool for prediction of the surface hydrology of khet terrace systems in more realistic situations.

One storm event was monitored on both systems (with the help of a Nepali field assistant) and two other storms were monitored on the 7 terrace system. The validation exercise was viewed in two ways. Initially, the model prediction was compared to field data for the top 4 terraces only for each event. This is reasonable for the purpose of validation as it provides a like-for-like comparison of the accuracy of the model predictions during the validation exercises vis a vis the model predictions during the calibration exercises. The accuracy of the model in predicting the reaction of the full 7 and 18 terrace systems was then considered to evaluate how the model performed in situations at the scale required if the model is to be of practical use.

7.3 Validation Terraces

Khet HB consisted of a set of 7 terraces, close to the field house and Khet HA. Khet PA consisted of 18 terraces and was situated on the opposite bank of the Likhu Khola, about 1.5 km distant (the location shown on Figure 3.5). Terraces within both sets were linked linearly.

On Khet PA the terraces were approximately rectangular and though some were of irregular shape all had good internal flow lines. On Khet HB the terraces were of irregular shape but again all had good internal flow lines. Tables 7.1a and 7.1b give terrace areas.

Tables 7.1a and b – Khet HB and Khet PA Terrace areas.

Terrace	Area (m^2)
HB1	42.69
HB2	8.06
HB3	8.51
HB4	12.26
HB5	7.1
HB6	19.54
HB7	24.22

a)

Terrace	Area (m^2)
PA1	22.5
PA2	30.75
PA3	59.5
PA4	20.0
PA5	76.25
PA6	46.5
PA7	16.25
PA8	42.75
PA9	94.5
PA10	88.0
PA11	128.25
PA12	156.75
PA13	172.25
PA14	105.5
PA15	230.0
PA16	88.5
PA17	41.5
PA18	36.75

b)

7.4 Validation Storm Events

Three discrete storms were monitored on Khet HB, one of these was also monitored on Khet PA. The magnitude of the storm events varied from 23.9 mm to 45.8 mm, the duration from 107 to 292 minutes, maximum intensity from 44.4 mm/hr to 88.8 mm/hr. Monitoring periods for the events, and thus model application durations, varied from just under 3 hours to 9 hours and 10 minutes.

Ideally, events would be monitored from shortly before the start of rainfall, through the peak of the rainfall event, during the falling limb and until such time that the system had reverted to similar levels as the start conditions or was at or close to a new equilibrium. As is noted in Table 7.2, describing individual storm events below, this was not possible in two instances. However, sufficient data were obtained to allow comparison to model predictions. It should also be noted that the system is one of dynamic equilibrium and the normal condition is that it is slowly altering towards a changed equilibrium position, particularly when irrigation levels have been changed by rainfall. As such, it could never truly be stated that the system reverts to its pre-event position. Table 7.2 summaries the event characteristics and Figure 7.1 shows relative storm intensity.

Table 7.2 Storm Characteristics

Event	Rainfall Duration mins	Magnitude mm	Max Intensity mm/hour	Irrigation Start l/min	Peak l/min	End l/min	Model Duration mins
Jul-17	395	34.4	44.4	0	8	0	660 *1
Jul-19	139	23.9	88.8	0	240	2	460 *2
Aug-3 HB	410	45.8	60.0	0	200	68	460 *3
Aug-3 PA	410	45.8	60.0	0	186	14	460

Notes:
*1 Event also monitored on Khet HA during calibration
*2 Rising limb only
*3 Rising limb only

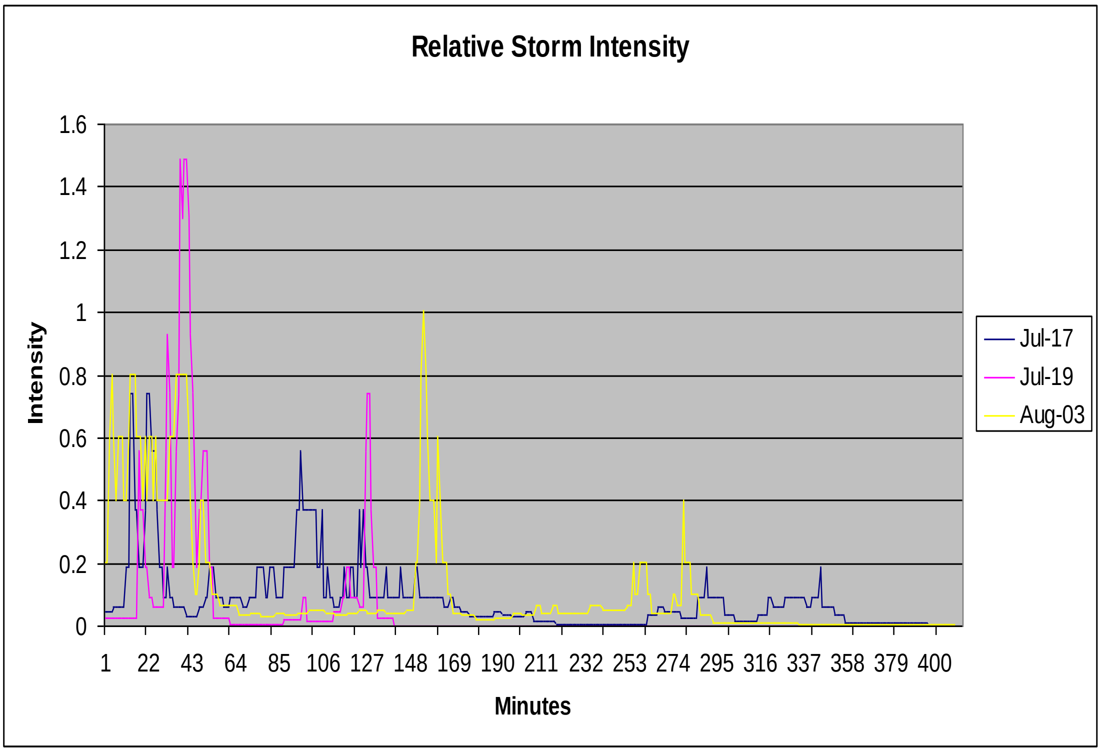


Figure 7.1 Comparison of Intensities of the Validation Storms

7.5 Validation Procedure

To validate the model the field measurements for each of the above events were compared with values predicted by the Khetflow Model when using the same data for rainfall and irrigation inflow, together with the net parameter value of 73 ml/m^2/min for evapotranspiration, seepage and return flow, as determined by the calibration procedure in Chapter 6.

The field measurement techniques are described in Chapter 4. For each event this provided rainfall intensity and data for each terrace for irrigation, inflow and outflow and water depth and volume. Rainfall was recorded per minute, terrace data were recorded periodically and converted to a resolution of 1 minute by straight line averaging and evapotranspiration, seepage and return flow values were transformed to a resolution of one minute.

Thus, as described in Chapter 6, data with a resolution of one minute for each of the variables allowed a hydrograph for each terrace to be constructed for each validation event. Figure 7.2 provides an example, the dark blue line represents the field values on terrace HB1 for the storm of July 17th. The light blue and yellow lines, parallel to and above and below the field value line represent values +1cm and -1cm respectively of the field values for terrace water depth, to help judge the accuracy of the model prediction. The model was used to predict each event to the same resolution and the model prediction hydrograph was compared to the hydrograph obtained from field measurements. The model prediction hydrograph is shown as the red line in Figure 7.2.

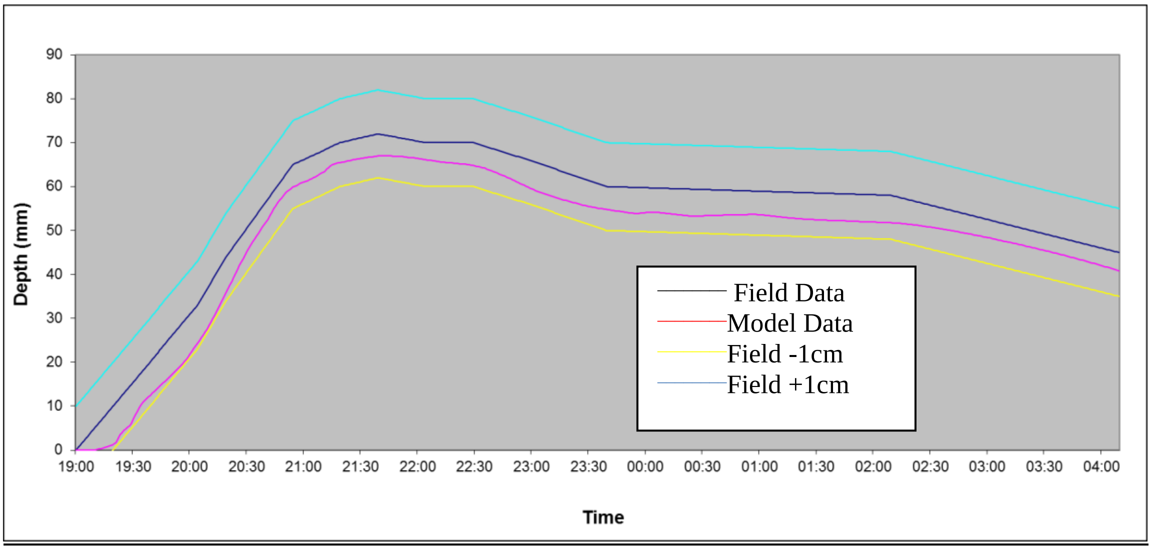


Figure 7.2 Example of Hydrograph Comparing Field and Model Values

The method used to assess the accuracy of the model data when compared with the field data for calibration purposes is described in detail in Section 6.4 and the same principles are used here. Mathematical calculation of a least squares 'score' was performed and visual comparison of the respective graphs was again undertaken to confirm that the least squares assessment was reasonable.

As with the calibration events, the computations of the 'Least Squares per Minute' figure and the 'Whole System Value' were used as a basis for comparing field and model values but a further calculation was required to judge whether the model is validated by these tests. This was to ensure that the values obtained from the calibration exercise retain validity when applied in new situations for validation. Initially, the model prediction was compared to field data for the top 4 terraces only for each event. This is reasonable for the purpose of validation as it provides a like-for-like comparison of the accuracy of the model validation predictions vis a vis the model predictions during the calibration exercises on a 4 terrace system. However, 'Whole System Values' for least squares, which are the sum of least squares for all terraces in the system, are obviously going to be much higher in systems of seven and eighteen terraces than in a four terrace system so, when subsequently comparing the full systems, the 'Whole System Value' is divided by the number of terraces to give a

'Terrace Mean System Value' for each system. As explained in Section 4.8, least squares values are presented without dimensions.

The problems in using a least squares method, noted in section 6.4, again apply and the need for visual comparison of the hydrographs is re-stated. The need to relate the difference between model data and field data to the scale of field values is emphasised and the results should be considered in the context of reasonable field data error margins in the circumstances prevailing when monitoring took place. During the calibration exercise many model predictions were within 5mm of field data. Figure 6.2 plots a margin of 5mm as error bars aligned to the field measurements and shows how small changes in depth measurements translate to differences in volume. Results from the validation exercise were not as accurate as those from the calibration procedure. This might be expected as the ability to adjust parameters to obtain best fit gives degrees of freedom not possible during validation. Error margins were increased to 1cm (see Figure 7.2) but this can still be considered accurate in the context of the scale of the systems being measured and the field measurement problems previously described. In the example shown in Figure 7.2 (the validation exercise utilising the July 17th application on the HB terraces) the model prediction fits completely within the 1cm field error margins.

During the calibration exercise it was stated that a least squares mean of 25 or less for any terrace represented a mean divergence of 5mm or less between the two sets of data, reflecting the error margins previously reported. The corresponding least squares mean representing the 1cm error margin for the validation is 100 or less.

7.6 Validation Input Variables and Parameters

The input variables and parameters used in the validation of the Khetflow Model are:

Initial Store level (l)
Rainfall (mm/min)
Irrigation Inflow (ml/min)
Net loss from Evaporation, Seepage and Return Flow (ml/min/m^2)

Rainfall and irrigation inflow are the ‘drivers’ of the system and have been determined by accurate field measurement. Net loss from Evaporation, Seepage and Return Flow was determined by calibration as 73 ml/m^2/min

7.7 Validation Results

7.7.1 Validation Results Format

The validation results were reviewed in three ways:

1. The most straightforward consideration of the validation tests is to compare the accuracy of the validation prediction for the top four terraces with the accuracy of the results obtained from the four terrace system during calibration. Ideally, the accuracy of the validation results would match that of the calibration exercise and this is the closest like-for-like comparison.

2. The accuracy of the validation prediction for the full set of terraces for each event is then compared to the accuracy obtained during calibration by calculating a terrace mean for each system.

3. The accuracy of the validation predictions are then reviewed in their own right, both from the point of view of the least squares scores and review of the actual hydrographs produced. Here the hydrographs are compared to field measurement errors of 1cm and comment is made about the least and most accurate terrace prediction for each event. Whilst the accuracy of the validation results is varied, almost all fall within the 1cm field error margin and, importantly, accurate predictions are achieved for many lower terraces, sometimes more accurate than for terraces higher in the system.

7.7.2 Validation Predictions versus Calibration Predictions – Top Four Terraces

To compare the accuracy of the validation and calibration exercises the top four terraces from the validation predictions are compared with the results from the calibration prediction, in tables 7.3 and 7.4. The calibration exercise determined that the optimum value of Net Loss was 73 ml/m^2/min. At this value the least squares scores for the storms measured for calibration (excluding the 11th July event, when only 3 terraces were valid) are reported in Table 7.3.

Table 7.3 Least squares scores obtained during calibration at optimum model values

Storm Event	Least Squares (total 4 terraces)
13/7	131
16/7	93
17/7	89
30/7	39
31/7	30

Table 7.4 Least squares scores obtained during validation at optimum model values

Storm Event	Least Squares
17/7 (HB)	218
19/7 (HB)	154
3/8 (HB)	129
3/8 (PA)	348

Using the value for net Loss determined by calibration, the least squares scores for the top 4 terraces during the validation storm events are reported in Table 7.4.

Clearly, in these circumstances the model predictions from the validation exercise are not as accurate as those recorded during calibration. The accuracy of the two of the validation events on the HB terraces are better than the two worst calibration results and the results for the PA terraces are worse than for any of the calibration storms. However, inspection of the results in greater detail is more encouraging, as is discussed below in Sections 7.7.3 and 7.7.4.

7.7.3 Validation Prediction versus Calibration Prediction – Full Terrace System

Tables 7.5 and 7.6 again present the results for the calibration and validation exercises, respectively, but also report the full 7 and 18 terrace systems for the calibration and include calculation of the terrace mean of the least squares for each event. This shows improvement in the validation scores and that the accuracy for the HB terraces is closer to that of the calibration exercise. As accuracy is greater when all 7 terraces are included rather than just the top 4, it suggests that during the validation exercise the accuracy of the lower terrace predictions was better than that for the top terraces.

Table 7.5 Least squares scores obtained during calibration at optimum model values

Storm Event	Least Squares (total 4 terraces)	Terrace Mean
13/7	131	33
16/7	93	23
17/7	89	22
30/7	39	10
31/7	30	6

Table 7.6 Least squares scores obtained during validation at optimum model values

Storm Event	Least Squares	Terrace Mean
17/7 (HB)	330	47
19/7 (HB)	254	36
3/8 (HB)	205	29
3/8 (PA)	2207	123

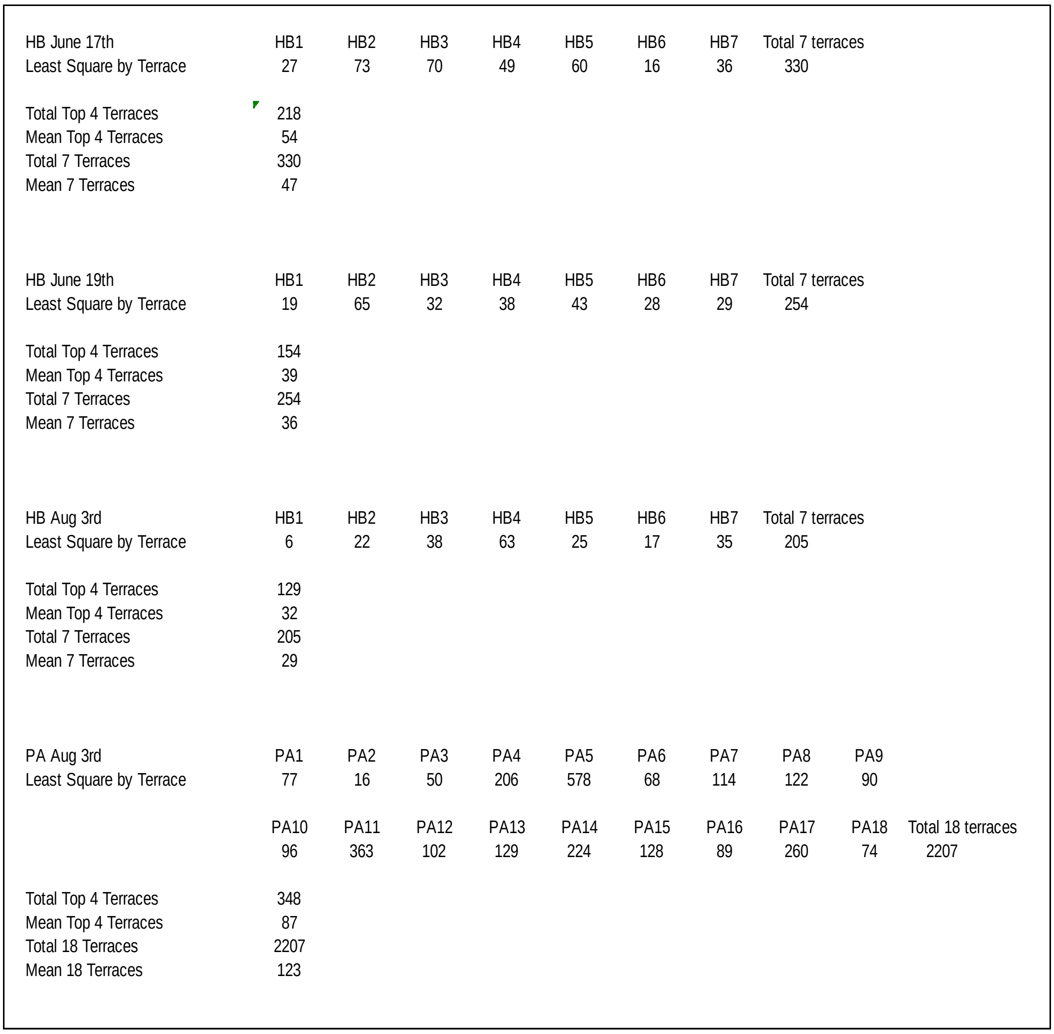
Ideally, the model provides accurate predictions for all terraces but the accuracy of the results of the lower terraces are more important because of the structure of the system. The linear hierarchy dictates that one of the main components of the hydrological behaviour of any particular terrace is the behaviour of the terraces above that terrace, particularly the terrace immediately above. In turn, the behaviour of each terrace has an influence on all the terraces below, particularly the one immediately below. This hierarchy is at the heart of the design of the Khetflow model; each minute the change in volume of water in one terrace is measured and the change of depth calculated. This is reflected in a change in flow height across the terrace weirs and thus a change in water volume flowing into the terrace below.

In Chapter 2 it was explained that this change would cascade down the terrace system in a cumulative manner and in Chapter 5 the Khetflow model was shown to have high sensitivity to such changes, particularly in terraces at the bottom of the khet systems. It has also been explained that this is reflected in the field by the architecture of the terraces – terrace systems are generally restricted to 10 to 30 terrace “drops” between irrigation canals because the farmer is aware that in longer systems the lower terraces will flood during storms, causing damage to both crop and terrace structure. As is explained below, if the model predictions for a few individual terraces are poor but the predictions generally, and particularly for the terraces lower in the system, are good it is more likely that the poor predictions are the result of inaccurate field measurements rather than model inaccuracies.

7.7.4 Validation Predictions for Each Event

The validation results are now considered in more detail, by individual events. On the HB and PA terraces events this is undertaken with particular reference to the individual terraces where the Khetflow Model gave the most accurate and least accurate prediction in terms of the least squares scores for each of the validation storm events. These are shown in Figures 7.3 to 7.6, which also include the 1 cm field error margins. Discussing every terrace for every event would be repetitive and of little use, relevant points can be adequately made by comparing the two extremes for each event with appropriate references to the full set of hydrographs. Raw data produced by the model during validation, the calculation of least squares and generation of the hydrographs was achieved by the methods described in Section 4.8.; the least squares scores for the full terrace system and for individual terraces are given in Table 7.7.

Table 7.7 Least Squares Scores for Individual Terraces



HB June 17th	HB1	HB2	HB3	HB4	HB5	HB6	HB7	Total 7 terraces
Least Square by Terrace	27	73	70	49	60	16	36	330
Total Top 4 Terraces	218							
Mean Top 4 Terraces	54							
Total 7 Terraces	330							
Mean 7 Terraces	47							

HB June 19th	HB1	HB2	HB3	HB4	HB5	HB6	HB7	Total 7 terraces
Least Square by Terrace	19	65	32	38	43	28	29	254
Total Top 4 Terraces	154							
Mean Top 4 Terraces	39							
Total 7 Terraces	254							
Mean 7 Terraces	36							

HB Aug 3rd	HB1	HB2	HB3	HB4	HB5	HB6	HB7	Total 7 terraces
Least Square by Terrace	6	22	38	63	25	17	35	205
Total Top 4 Terraces	129							
Mean Top 4 Terraces	32							
Total 7 Terraces	205							
Mean 7 Terraces	29							

PA Aug 3rd	PA1	PA2	PA3	PA4	PA5	PA6	PA7	PA8	PA9	
Least Square by Terrace	77	16	50	206	578	68	114	122	90	
	PA10	PA11	PA12	PA13	PA14	PA15	PA16	PA17	PA18	Total 18 terraces
	96	363	102	129	224	128	89	260	74	2207
Total Top 4 Terraces	348									
Mean Top 4 Terraces	87									
Total 18 Terraces	2207									
Mean 18 Terraces	123									

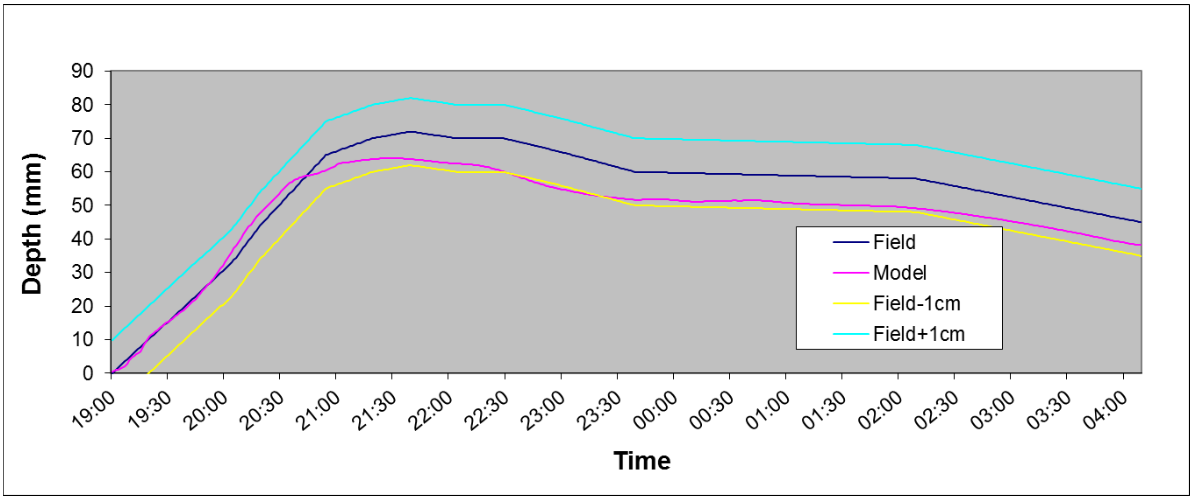
In the broader sense there can only be two reasons why field and model data are not equal; either the field data are inaccurate or the model is flawed (or it is a result of some combination of the two). The Sensitivity Analysis showed that the system will only operate within a narrow range of environmental variables and that the system breaks down if these variables are assigned values that deviate too far from those prevailing. Because of the hierarchical nature of the model, if the design was flawed it would be expected that if the predictions for the top terraces were incorrect the results would get increasingly worse as the errors were cascaded down the system and multiplied.

Accurate model predictions for terraces lower in the system shows this is not the case and it is suggested that the main cause of error is inaccurate field measurements for individual terraces or unrecorded leaks into or out of terraces. The general conditions in which measurements were taken have been described in Section 4.3 and measurements for 3 of the 4 validation events had to be taken during the night. The results from some of the individual terraces in Khet PA, discussed below, reflect these problems.

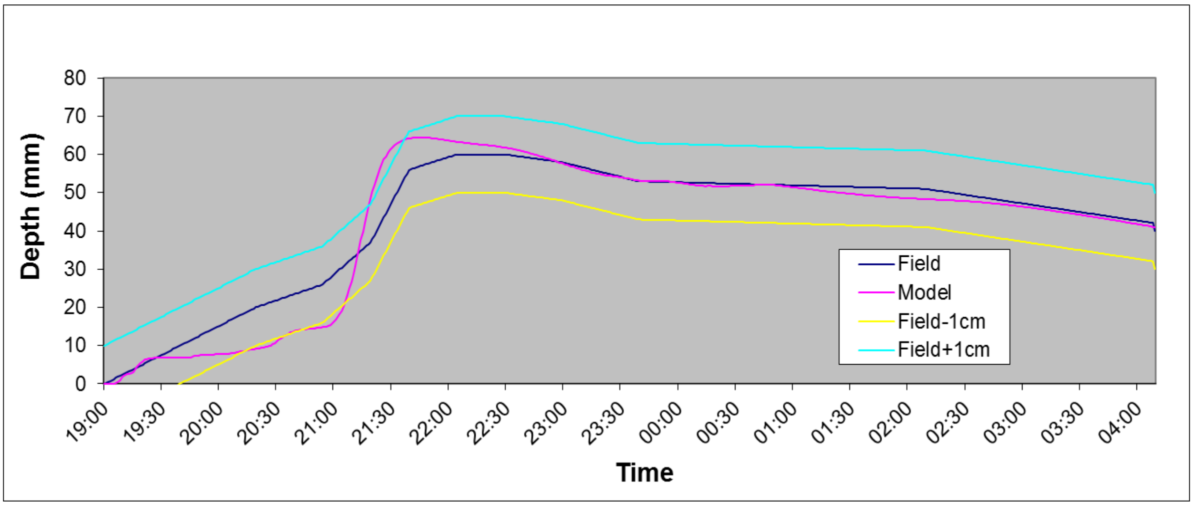
More detailed analysis of the results also shows that whilst the validation results do not match the accuracy of the calibration results, in the context of the systems being monitored they are still within the bounds of reasonable accuracy. During the calibration exercise many of the results showed that the Khetflow model was correctly predicting the behaviour of terraces within a margin of 5mm of field measured water depth for the whole of the storm event. In the field circumstances described this can be regarded as extremely accurate. The margins of error during the validation exercise are still, in almost all cases, within 1 cm of field measured water depth. This can also be considered accurate under the prevailing field conditions.

The July 17th event was the least well predicted of the validation events on the HB terraces but accuracy was still within reasonable error margins. Figure 7.3a and 7.3b show the hydrographs for the most and least accurate terraces for this event, these being the top and second terraces respectively. The light blue and yellow lines represent the plus and minus 1cm field error margins. For the hydrograph with the best result, HB1, the model prediction is very accurate, reflecting very well the shape of the field hydrograph, though constantly under reporting by a small amount. This illustrates the importance of considering the hydrographs visually to provide a more complete analysis, which is also the case for the hydrograph provided the worst prediction of field data. In HB2 the rising limb is not well predicted by the model but the shape of the falling limb is well matched, though slightly over recorded, thus inflating the least squares scores.

For the reasons given above it is reassuring that the bottom two terraces were the second and third most accurate.



(a)



(b)

Figure 7.3a and 7.3b Hydrographs of the HB terraces with Highest and Lowest Least Squares Scores, including 1 cm error margin, for the 17th July Storm.

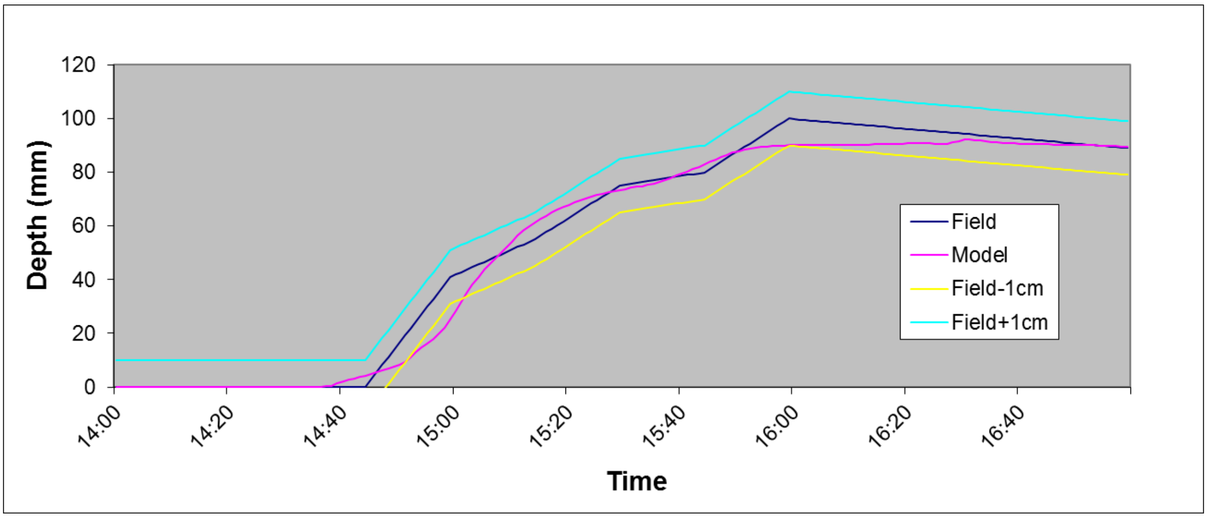
Hydrographs of the model prediction for each of the seven terraces for this validation event (illustrated in Appendix A2) give reasonable levels of accuracy when compared with field data, mostly contained within the 1cm margin. The least squares average also falls within the 1 cm error margin for all seven terraces.

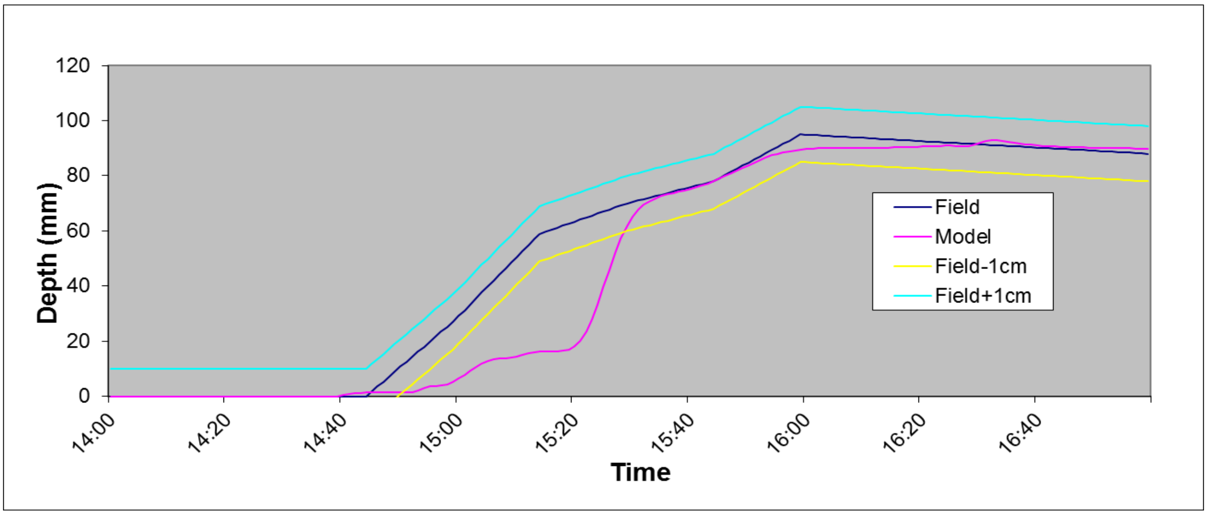
Figure 7.4a and b shows the hydrographs for the most and least accurate terrace results by the least squares method for the July 19th event on Khet HB and once more these are the top terrace the top and second terraces, respectively. The light blue and yellow lines represent the plus and minus 1cm field error margins.

In Figure 7.4a the model prediction for terrace HB1 is a good replication of the field data, the prediction line lies almost completely within the 1cm lines (apart from a brief period early in the event) and the shape of the field hydrograph is well mapped. For HB2 the second half of the field hydrograph is accurately predicted but the first half is not, the model prediction considerably understating the field data during this time. The predictions for the remaining five terraces are remarkably consistent, least squares scores only varied from 28 to 43 for these five terraces and again the least squares average falls within the 1 cm error margin for all seven terraces. The predictions for the lowest two terraces were once more the second and third most accurate.

The tendency for the model to under-predict the field data during the first half hour or so of an event is again seen on almost all terrace hydrographs. The August 3rd event provided the most accurate prediction of the validation events on the HB terraces. Figures 7.5a and 7.5b show the hydrographs for the most and least accurate terrace results by the least squares method for this event. The most accurate prediction is again HB1 (the top terrace) but HB4on this occasion provides the least well predicted result. For this event several other terraces provide predictions almost as accurate as HB1 and again the predictions (apart from HB1) are more accurate in the lower terraces. The light blue and yellow lines again represent the plus and minus 1cm field error margins.

In Figure 7.5a the model prediction for terrace HB1 is once more a good replication of the field data, the prediction line lying completely within the 1cm lines and would be mostly within a 5mm error margin. The shape of the field hydrograph is well mapped, although the field data are consistently (but marginally) understated. Once more, the least squares average falls within the 1 cm error margin for all seven terraces.

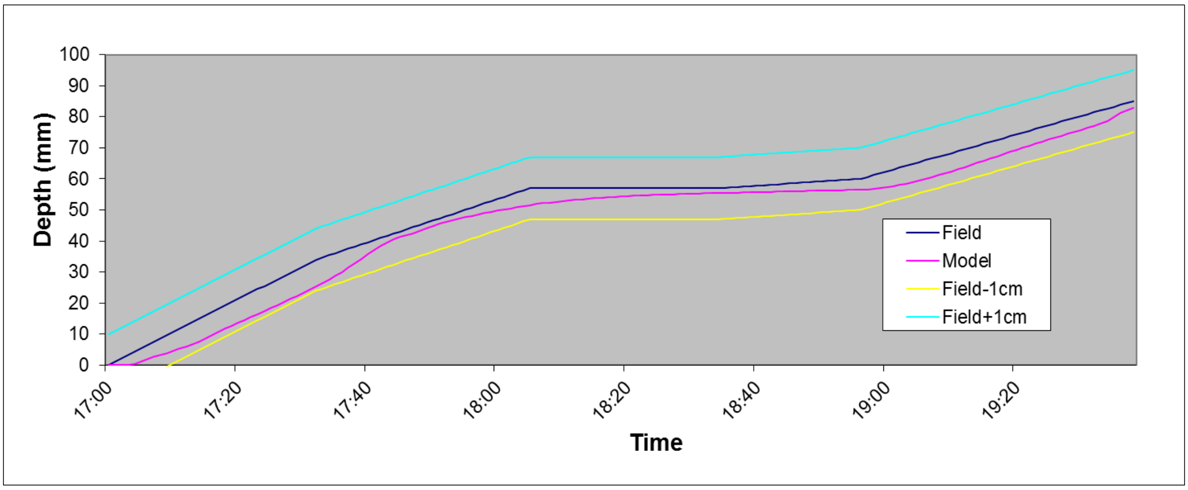




Figures 7.4a and 7.4b Hydrograph of the HB terraces with Highest and Lowest Least Squares Scores, including 1 cm error margin, for the July 19th Storm.

Terrace HB4 provides the worst prediction but in this application even the worst prediction has acceptable accuracy, apart from early under recording and until tailing off in the final quarter of the monitored period. In this storm the relative inaccuracy of HB4 is an anomaly and on the other five terraces the predictions are again consistently accurate, with a least squares score range of between 17 and 38.

It may simply be coincidence that the top two terraces provide the best and least accurate predictions in the first two applications on the khet HB terraces (and that HB1 also provides the most accurate prediction in the third application); and that the lowest two terraces are consistently within the most accurate. That there are similar patterns could also reflect a systematic field bias, particularly at the point of inter-terrace flow between the top two terraces where inaccuracy in HB2 is of a consistent nature.



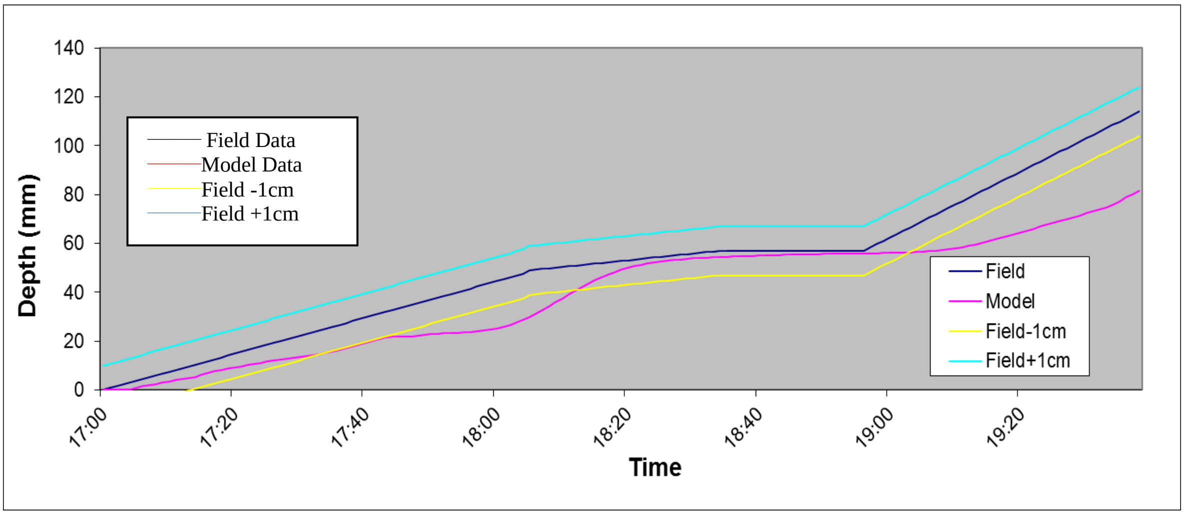


Figure 7.5a and 7.5b Hydrograph of the HB terraces with Highest and Lowest Least Squares Scores, including 1 cm error margin, for the August 3rd Storm

The results for Khet PA were inconsistent in that for some terraces extremely accurate predictions of the event are given by the model but these are interspersed with poor replications of field values. Khet PA was monitored for seven and a half hours during the August 3rd storm. The least squares scores for the full terrace system and for individual terraces are given in Table 7.7 and hydrographs are shown in Appendix A2.

It is suggested above that an inaccurate prediction is either caused by a flaw in the model or inaccurate fieldwork, or a combination of the two, and that a strong indication of where the fault lies is provided by the accuracy of the prediction on terraces lower in the system. If the model is flawed then errors would be cascaded down the system and none of the lower terraces would be replicated satisfactorily. If some terraces, particularly lower in the system, have accurate predictions then it is likely that errors have occurred in data collection in terraces with inaccurate predictions, as is discussed below. Table 7.7 shows that 43% of the error in this eighteen terrace system comes from just two terraces, PA5 and PA11, and that another 31% of the error is recorded in a further three – PA4, PA14 and PA17. Thus, 74% of the error is accounted for in the worst five terraces whilst the model provides accurate predictions for adjacent terraces. The five worst terraces are distributed throughout the khet system (terraces are numbered sequentially, PA1 being the highest).

It would seem likely, therefore, that terraces PA5 and PA11 have not been monitored accurately in the field. If this measuring error was caused by unmonitored leaks from the terrace above or into the terraces below it would be expected that there would be a corresponding and opposite error in the data for the relative adjoining terrace. This is not the case. As can be seen the hydrographs in Appendix 2, early monitoring is accurate, followed by a huge shift in the field data vis-à-vis the model prediction, followed by accurate replication of the shape of the field hydrograph but at widely differing volume levels. In the case of terrace PA5, in the latter two thirds of the event model values are approximately 4 times those measured in the field; in the case of PA11, field values are approximately twice the value of those predicted by the model during the same period. The most obvious explanation for this is that the depth gauge (a bamboo cane with cm intervals painted on it fixed into the terrace mud) has been accidentally moved and the correct relative amount of depth change (and thus volume) is being recorded, thus mapping the correct shape of the hydrograph but at a higher (in the case of PA11) or lower (in the case of PA5) absolute value. The same pattern can be seen for the other three terraces for which the model makes a particularly poor prediction – PA4, PA14 and PA17. For the remaining thirteen terraces the model provides reasonable predictions of field data. The most encouraging aspect of the results from this event is that again several of the lower terraces provide accurate predictions.. The importance of this, that this would not be possible if the model had a basic flaw, has been explained above.

7.8 Summary of Validation Exercise

Model predictions of the events used for validation have not been as accurate as those for calibration but events have been replicated with sufficient accuracy to confirm the value of the model in predicting the flow of storm water through khet terrace systems. The accuracy of the prediction of terraces lower in the khet systems indicates that when model predictions are less precise the error lies with the field data and not a systematic flaw in the model. Field data were mostly collected in adverse conditions and in such circumstances model predictions of terrace water depth that are within plus or minus 1cm of field recordings, as is the case for most of individual terrace events, can be considered acceptable.

Chapter 8–Modelling Khet Systems During and After Storms

8.1 Introduction

This chapter pulls together several threads from the previous chapters and examines them in greater detail in the context of realistic situations on khet systems; to define how best to use the model to better understand the surface hydrology of khet hillslopes in a practical and pragmatic manner and then to deploy the model to that end. Following on from the sensitivity work reported in Chapter 5, it commences by examining different designs of multi-terrace khet systems to find a configuration that allowed the maintenance of water balance during 'normal' frequency monsoon storms and thus provides a workable system as the structure for the remainder of the research. Once a workable system has been 'designed', how best to deploy the model for the remainder of the research is considered, bearing in mind the constraints imposed by the realisation that systems only operate within a narrow range of variables because of the need to maintain the water balance. Just as importantly, this section considers what is impractical or unworkable. Finally, the model is deployed in different situations:

(i) to speculate as to the reaction of khet systems to monsoon storms of varying size and frequency;
(ii) to speculate as to the breaking point of the system;
(iii) to test methods that might ameliorate the breaking point of the system;
(iv) to test the buffering capacity of the terraces during storms;
(v) to speculate as to terrace system contribution to quickflow during and after storms.

Three storms were simulated to model the 25 'drop' terrace system during the sensitivity work and the same three storms are employed throughout this chapter.

They are referred to as follows:

Standard Storm: Rainfall of 1mm per minute for one hour, total 60 mm rainfall, utilised during much of the Sensitivity Analysis in Chapter 5. A storm of this magnitude would be expected 2 to 4 times per monsoon in the Likhu Khola but may exceed 20 times per year in the Modi Khola (see below).

Heavy Storm: Of the same intensity as the standard storm but twice the duration, rainfall of 1mm per minute for two hours, total 120 mm rainfall, representing a heavy storm but still well within normal frequency during a monsoon season in many parts of Nepal. A storm of this magnitude would be expected 0 to 2 times per monsoon in the Likhu Khola but may exceed 8 times per year in the Modi Khola (see below).

Extreme storm: Of twice the duration and intensity of the standard storm, rainfall of 2mm per minute for two hours, total 240 mm rainfall. A storm of this magnitude would only occur very rarely in the Likhu Khola but is projected to occur 3 to 5 times a monsoon season in the Modi Khola (see below) and reflects storms that are likely to cause system breakdown in the field.

Storm frequencies for the Likhu Khola are taken from Gardner and Jenkins (1995) and for the Modi Khola from Mawdesley and Gardner (1997). This research was undertaken in the Likhu Khola valley but when applying the model speculatively, particularly when testing breakdown limits, it is appropriate to include storm of a magnitude found in areas of Nepal where the monsoon is heavier.

8.2 Review of Khet Terrace Configurations

8.2.1 Testing Different Terrace Configurations: Method

Model applications to analyse system sensitivity reported in Chapter 5 revealed that a terrace system consisting of 25 drops but with only one outlet per terrace provided for an unworkable system that could not reflect the reality of the field situation. Terrace area / outflow ratios needed to be adjusted to attain the required water balance to make the system operable and experiments were conducted on terrace systems with different configurations of terrace outflows to achieve this. Experiments were conducted varying both terrace area and number of outflows but, as is discussed later in the chapter, an arbitrary decision as to terrace area was required. To maintain continuity with the previous work on sensitivity, it was thought appropriate to adjust the terrace area / outflow ratio by retaining the same terrace area and adjusting the number of outflows. Outlet width remained the same as for the previous work and increased terrace outflow was achieved by increasing the number of outflows. The same effect could have been realised by increasing outlet size (or a combination of increasing size and number). However, the aim is to find the correct ratio of water that needs to be shed to keep the system in balance and it doesn't matter in what manner the outflows are adjusted to achieve this. The size of outflow for which a calibrated value for depth to outflow rate had been measured was retained. As is seen below, the difficulty in finding a workable system configuration once again illustrated the fine margins under which the system operates and the control thus exerted on terrace design.

To design a workable terrace configuration initially the outflows from the terraces (and thus inflows to the terrace below) were increased in a linear manner throughout the system. Experiments were conducted with each terrace having two and then three outflows. Matching field practice, experiments were then conducted on systems designed to have a greater number of outlets in the terraces lower in the system. Systems where outlets were augmented from 1 outlet in the higher terraces to a maximum of three, four and five outlets at the bottom of the system were designed (five outlets along the width of a ten metre bund was considered the maximum practical in the field). When systems were designed in this manner the terraces which had the same number of outlets were proportionally equal, e.g. if the maximum number of outlets was 3, terraces 1 to 8 had 1 outlet, terraces 9 to 16 had two outlets and terraces 17 to 25 had 3 outlets.

The same model applications as on the 25 terrace x 1 outlet system were tested: the standard storm; the heavy storm of the same intensity and twice the duration; and the extreme storm with twice the duration and intensity. The heavier storms were applied because the terrace system had to be shown to be in balance and operable in storms at the high end of the normal monsoon storm frequency range to be said to be a valid representation of the field situation, which it is reasonable to assume has evolved to cope with such heavy storms. The capability of the different system configurations to deal with the three storms was judged by three criteria:

- Peak depth
- Peak outflow
- Length of time water depth was greater than 10cm.

Peak depth and peak outflow needed to be comparable to field measurements to be realistic. It was noted in Chapter 5 that field measurements where terrace depths greater than 10cm during storms were recorded but not often encountered. Inter-terrace flow rates of 500 l/min were never encountered. Excessive water depths introduce the danger of bund failure and resultant terrace damage and ideally water needs to be shed from terraces quickly. For the purpose of this experiment, water depth of greater than 10cm was taken as the boundary level above which there was danger of bund failure. There is no conclusive depth at which bund failure or terrace overtopping could be said to definitely happen but depth levels over 15 cm are likely to be unsustainable. Experiments with multi-terrace systems have already shown that terrace reaction increases cumulatively down the system so for these experiments measurements from the bottom terrace in the system were compared as this would reflect the most extreme reaction.

When reporting these applications the system configurations are denoted as follows:

T25x1:	25 linear terraces with one outlet per terrace
T25x2:	25 linear terraces with two outlets per terrace
T25x3:	25 linear terraces with three outlets per terrace
T25x123:	25 linear terraces augmented to a maximum of three outlets per terrace

T25x1234: 25 linear terraces augmented to a maximum of four outlets per terrace
T25x12345: 25 linear terraces augmented to a maximum of five outlets per terrace

The raw data produced by these model applications was processed as explained in Section 4.8 and the results reported below then extracted.

8.2.2 Testing Different Terrace Configurations: Results

Table 8.1 shows that all system designs tested were able to absorb the standard storm with little difficulty, although the terraces with uniform numbers of outlets less so than the ones with augmented outlets.

Table 8.1 Comparison of Results for 25 Terrace Systems of Different Designs – Standard Storm

Terrace	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)
T25x1	10.0	261	101
T25x2	9.8	250	n/a
T25x3	10.1	263	66
T25x123	8.9	214	n/a
T25x1234	8.2	188	n/a
T25x12345	8.6	203	n/a

Testing the capacity of the different terrace designs to absorb a heavier storm was more instructive. Table 8.2 provides a comparison between the different system designs when subjected to a storm of twice the duration of the standard storm. Uniformly increasing terrace outlets so that every terrace had two and three outlets produced mixed results. In the system with only one outlet (T25x1) in the lowest terrace, peak depth was 15.9 cms, peak outflow 483 l/min and there was in excess of 10cms depth for 590 minutes. In the two and three terrace systems (T25x2 and T25x3), excess water time reduced to 269 minutes and 178 minutes, respectively, but peak depths and outflows both increased. This reflects the water being shed from the upper terraces more efficiently but still backing up in the lower terraces, which cannot cope with the increased influx.

The three configurations increasing the number of outlets so that there were more in the lower terraces each brought improvement. The system designed with a maximum of four outlets in the lower terraces (T25x1234) proved the most efficient and most realistic when compared to maximum field values. All systems provided a reduction in peak depth and outflow and considerable reduction in the time taken to shed excessive water from the system. The T25x123 and T25x12345 terrace configurations reduced peak depths to 13.5 cms and 13.4 cms respectively; peak outflow to 413 l/min and 411 l/min respectively and time with greater than 10cm depth to 109 minutes and 92 minutes respectively. However, the most satisfactory result was achieved on the T25x1234 design, which absorbed this heavy storm with the lowest terrace reaching a depth of only 11.6 cm and outflow rates of 330 l/min. There was excessive water in the bottom terrace for only 54 minutes.

Table 8.2 Comparison of Results for 25 Terrace Systems of Different Designs – Heavy Storm

Terrace	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)
T25x1	15.9	483	590
T25x2	16.4	547	260
T25x3	16.9	574	178
T25x123	13.5	413	109
T25x1234	11.6	330	54
T25x12345	13.4	411	92

It had been intuitively expected that increasing the maximum number of outlets from four to five would have caused an improvement in the efficiency of the system but as can be seen in Table 8.2, this was not the case. Quicker draining of water from the higher terraces provided a less efficient situation in the lower terraces and water backed up there. This powerfully illustrates the narrow margins within which the system operates efficiently.

Finally, the three configurations where the outlets were augmented lower in the system were tested against the most extreme storm, with twice the duration and intensity of the standard storm. However, this produced results that were difficult to evaluate. It is appropriate to note that such a rainstorm would almost certainly strain the physical system beyond breaking point and as such it is difficult to model this accurately. There is usually some terrace breakdown and overflow during the monsoon season, which obviously occurs in the heavier storms. The heaviest storm to be tested here represents the one of the heaviest monsoon storms likely to be encountered and so reflects storms that probably cause system breakdown in the field. If the physical system cannot cope with such a storm then it is to be expected that the model reflects this breakdown in some manner.

Table 8.3 Comparison of Results for 25 Terrace Systems of Different Designs – Extreme Storm

Terrace	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)
T25x1	29.1	1205	660
T25x123	24.4	945	226
T25x1234	20.5	749	183
T25x12345	23.7	915	184

Table 8.3 summarises the results of modelling this storm. All of the designs report values well in excess of those recorded in the field and without doubt reflect system breakdown. It can only be said that the system designed with a maximum of four outlets per terrace copes with the storm better than the other two designs, having lower peak depth, maximum outflow, and reporting less time (marginally in one case) with water depths of greater than 10 cms. T25x123 and T25x12345 reported maximum depths of 24.4 cms and 23.7 cms, respectively; maximum outflow of 945 l/min and 915 l/min, respectively, and time with depth greater than 10cm for 226 minutes and 184

minutes, respectively. T25x1234 recorded a maximum depth of 20.5 cms, maximum outflow of 749 l/min, and time with greater than 10cm depth 183 minutes. All figures that are better than the two linear designs but off the scale of anything encountered in the field. However, all results are also a considerable improvement on the original T25x1 design, which had peak depths of 29.1 cms, peak outflow of 1205 l/min, and 11 hours with water depths of over 10cms.

8.2.3 Testing Different Terrace Configurations: Summary

Because of the unsatisfactory performance of the original terrace system designed with one outlet per terrace, five further configurations were tested. Increasing outflows in a linear manner, to two and then three per terrace, improved results but not to the extent when progressively augmenting outlets throughout the system. Configurations augmented to a maximum of three, four and five outlets per terrace were tested. These results indicate that increasing outlets from one to a maximum of four lower in the system provides the system design most efficient at clearing excess water from the system after storms. As such this system is thought to be the closest representation of the field situation and will be the design used for hypothetical tests in the concluding part of this research described in Section 8.4. A caveat to this decision is that it assumed that the system of terrace design that has evolved in the field is at or near the most efficient at shedding water and there is no proof of this without further research.

To compare this system with previous sensitivity testing and, importantly, to test how long storm water remained in the 25 drop terrace system, the results for the standard storm were applied to the T25x1234 design and reviewed again. On the lowest terrace, peak depth was 8.2 cms (so lower than the 10cm depth selected as critical for the previous tests) and peak outflow 185 l/min. The time taken for the bottom terrace, and thus the terrace system as a whole, to return to the start position was 601 minutes. This means that under these conditions, if a second storm starts within 601 minutes of the first one ending, the reaction of the system to the second storm will be reinforced to some degree by the residue of the first storm, the extent of which would be determined by the actual timing of the start of the second storm. This provides the starting point for model experimentation with antecedent conditions, reported later in the chapter.

8.3 Implications of Terrace Design for Further Research

The above experiments with different configurations of khet systems consisting of 25 ‘drops’, representative of khet subsystems in the Middle Hills, strongly influenced the remainder of the research as this precluded experimentation with certain aspects of terrace characteristics. Testing the situations listed below were considered but a number were discounted from further deliberation, or the proposed experimentation was qualified, by the pragmatic insights gained during the overall research, particularly the narrow margins within which khet systems operate and the overriding control of the need to maintain a water balance in the system. The following situations were considered:

- Varying terrace area
- Varying terrace connectivity
- Varying the number of terraces
- Introducing the capability for lateral transfer between terraces at the same elevation
- Modelling partial emptying of the terraces by farmers adjusting outflow
- Quantifying the capability of the system to lose water via adjacent water courses
- Quantifying the buffering capacity of the terrace systems, particularly when they drain during longer inter-storm periods
- Modelling terrace reaction to variations in the size and frequency of rainstorms
- Analysis using factorial combination of some of the features referred to above

Modelling variations in terrace area and connectivity. Possible scenarios to be tested here are limited by the need to maintain water balance. Experimentation during the sensitivity analysis and above have shown that simply increasing or decreasing area or outflow capacity in isolation quickly resulted in terrace breakdown or draining if a reasonable area / outflow capacity ratio is not maintained. Conversely, increasing or decreasing area or outflow capacity whilst maintaining the area/outflow capacity ratio provided little change in the efficiency of the system and so there is limited scope for this type of experimentation.

Varying the number of terraces. The division of khet hillslopes into sub-systems consisting of 10 to 30 'drops' was explained in Section 3.4. The sensitivity analysis conducted on a 25 terrace system in Chapter 5 showed that terrace reaction was cumulative down the system. The reaction of terrace systems with fewer than 25 'drops' can be gauged by viewing the required number of the higher terraces in the 25 terrace system but this is not very informative as reaction is always less than that of the lowest terrace, the extent of which being dependent on how many terraces are selected. Model applications on a terrace system of 50 'drops' were undertaken but the pragmatic need to maintain water balance, meaning that a workable system could not be designed, resulted in the abandonment of this experiment.

Introducing the capability for lateral transfer between terraces at the same elevation. This scenario was not tested. If terraces are at exactly the same elevation, by definition there will not be flow between them unless artificially introduced. This could only happen if inflows from terraces above varied to adjacent, joined terraces. But this could only occur if the terraces were designed in such a manner, which would cause imbalance in the system and some terraces would drain. However, even if there was not a problem with water balance it is difficult to imagine terraces on exactly the same elevation being connected laterally to one another in the field. Introducing a bund in the middle of a large terrace that has no function to contain and pond water simply reduces growing area and gets in the way of ploughing. When the construction of terrace systems was described in Section 5.8 is was explained that the morphology of the hillslope may dictate that a large terrace could stretch over the land of two or more farmers and bunds would be constructed as land boundaries on adjacent terraces but these would be impermeable to normal surface flows, particularly as farmers would protect irrigation rights and are unlikely to share water. Terraces that are almost at the same elevation (perhaps a 15 cms drop between terraces) should behave in the same manner as other modelled khet systems. A system with a 15 cm drop between terraces will react in the same manner as one with drops of 115 cms except for the additional time it takes for water to drop 1 metre, which was considered to be an inconsequential time lag and is not a variable included in the model.

Modelling partial emptying of the terraces by farmers to adjust outflow. This scenario was also not tested as, from a pragmatic point of view, it would be too onerous for the farmer to undertake in a storm, particularly as fields may be away from the dwelling. From a modelling point of view the result would be totally in the control of the modeller. Any desired result could be obtained by the scale of the adjustment of the outflow or the position in the system it was executed. Of value would be to estimate the amount of water that needed to be shed from mid-points in the system, in order to contain the reaction of the terrace system, especially in heavier storms. This was achieved by the tests described below (Section 8.5) where outputs of modelling to test the capability of the system to lose water from mid-points of the system to adjacent water courses are presented.

Quantifying the capability of the system to lose water via adjacent water course. This can occur laterally to adjacent gullies or other land types; or to the irrigation canal (or other water course) immediately below the final terrace of the system. If farmers can shed excess water laterally from various points along the terrace subsystem to a nearby gully, the burden on the terrace system during storms, particularly heavy storms, should be lessened; and this ‘safety valve’ was tested. As is discussed below, this worked exceptionally well but, as is also discussed below, in reality the use of this method is usually impractical.

Of more interest is quantifying the water channelled into watercourses immediately it has exited the terrace subsystem as this then becomes quickflow to the river. Section 2.5 explained the division of khet hillslopes into discrete subsystems and that one of the main reasons for this was to prevent system breakdown because of the accumulation of water in the lower terraces during storms. The maximum number of terrace levels in a subsystem is normally 10 to 30 and rarely greater than 35. The primary purpose of irrigation canals is to provide irrigation water and it was unanticipated that the canals had a secondary, important function, to shed excess storm water from the systems to prevent breakdown. This must be the case, otherwise the water would overwhelm the subsystem below. It may be that deliberate channelling of storm water away from khet systems and into streams and gullies increases the quickflow component of rivers, promoting flooding (and at the same time, increasing the erosive power of smaller streams and contributing to excessive gullying; and reducing baseflow and thus water availability when it is most needed during the dry season). Section 8.6 describes the application of the Khetflow Model using both field data and speculative model data to predict the volume of water draining from khet systems during storms.

Quantifying the buffering capacity of the terrace systems. It is possible for terraces to drain during longer inter-storm periods, through a combination of drainage out of the system, seepage, evapotranspiration and the vagaries of irrigation availability. Irrigation availability can be a problem even in the monsoon which, as Figure 3.4 illustrates, can be imagined from the scale of khet rice production and the number of farmers vying for irrigation access. Farmers confirmed that the rice varieties grown in Nepal can survive up to two weeks without ponding, provided the soil remains damp. The terrace reaction to any storm will be muted if that is the case and in Section 8.4 predictions are made to quantify the extent of that.

Modelling terrace reaction to variations in the size and frequency of rainstorms. Many of the experiments tested by model applications in this research concerned terrace reaction to storms of differing intensity (the standard, heavy, and extreme storms). In this section this is considered in conjunction to variations in storm frequency. If the frequency of storms is such that a second or subsequent storm arrives before all the water from the initial storm has cleared the system, system reaction to the storm that follows will be reinforced by the antecedent position of the terraces. This section speculates as to the reaction of khet systems over longer time frames when monsoon storms are applied to the model in different situations.

Analysis using Factorial Combination. This approach was not tested, primarily because of the problem of water balance. Most of the factors that could be included in such analysis cannot be substantially amended in isolation without rendering the terrace system inoperable and nullifying the rationale behind the analysis. However, factors relevant to the pragmatic operation of khet systems, such as size and frequency of rainstorms, are analysed in depth in the sections following.

The remainder of the chapter concentrates on exploring the behaviour of the terrace system to the following four tests:

- Quantifying the Buffering Capacity of Drained Terrace Systems to Storms (Section 8.4)
- Quantifying the Capability of the System to Lose Water via Adjacent Water Courses (Section 8.5)
- Quantifying the Capability of the System to Lose Water via Irrigation Canals (Section 8.6)
- Modelling Terrace Reaction to Variations in the Frequency of Rainstorms (Section 8.7)

These tests attempt to determine which characteristics and situations are of most concern during monsoon storms on khet hillside, provide a robust and pragmatic examination of the ability of khet hillslopes to cope with storms during a variety of conditions, and identify important thresholds in the operation of these systems.

8.4 Quantifying the Buffering Capacity of Drained Terrace Systems to Storms

Terraces may drain during longer inter-storm periods. The terrace reaction to any storm will be muted if that is the case and such situations are modelled in this section. For the purpose of these applications the most efficient terrace configuration T25x1234 was assumed to have drained to empty in an inter-storm period when irrigation was not available. Because the terraces were no longer ponded, additional storage to a depth of 2.5 cm (the height of the base of the outflow above the terrace floor) has been created. Also, there would have been some drying of the soil so once the storm started the soil seepage rate was increased from 5 ml/m^2/min to 10 ml/m^2/min in recognition of this.

Each of the standard, heavy and extreme storms were then applied to test reaction, which was compared to previous results for this configuration when applied to the 'normal' start position of ponding, irrigation inflow and equilibrium. Table 8.4 provides the comparison between peak depth, peak outflow, and the time the lowest terrace contained excess water (>10cm depth). Additionally, the time taken after the storm starts for flow to be continuous throughout the system and the time taken after the storm ends for the system to return to the previous ponded equilibrium position is reported.

Table 8.4 Terrace Reaction to Storms when Initial Position is Empty

Event/ Terrace	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)	Continuous Flow (mins)	Stability (mins)
Standard Storm					
Ponded	8.2	185	n/a	n/a	601
Dry	6.3	113	n/a	25	573
Heavy Storm					
Ponded	11.6	330	54	n/a	619
Dry	10.3	274	13	25	605
Extreme Storm					
Ponded	20.0	728	230	n/a	651
Dry	19.1	679	203	12	650

The results show that the buffering capacity of empty terraces is surprisingly small. Also, the buffering capacity becomes less important as storms increase in magnitude, though this result might be expected as the buffering capacity is determined by terrace architecture, which remains static (as storms get more intense the ratio of the buffering capacity compared to the size of the storm decreases). The peak depth of the bottom terrace in the system decreased by only 1.9 cms, 1.3 cms and 0.9 cms for the standard, heavy, and extreme storms, respectively; and continuous flow through the whole terrace subsystem was regained at a maximum of 25 minutes after the onset of rain. Peak outflow was reduced by 39% in the standard storm but only by 17% and 7%, respectively, in the heavy and extreme storms and the time to regain the pre-storm stable position decreased only marginally, by 28 minutes for the standard storm; 14 minutes for the heavy storm and only 1 minute for the extreme storm.

The results suggest that empty khet subsystems have limited ability to buffer terrace reaction to storms, particularly in heavy storms, and quickly return to normal ponded operation after the onset of rain. This is discussed further in the concluding remarks in Section 8.8. The buffering capacity of the hillside during normal terrace operation is discussed in the next section.

8.5 Quantifying the Capability of the System to Lose Water via Adjacent Water Courses

This was modelled by adding extra outlets at mid-points in the terrace subsystem to drain excess water laterally to adjacent water courses (assumed here to be a nearby gully). This 'safety value' was very effective in the model but, unfortunately, in most cases is impractical in the field. Two experiments were undertaken on the T25x1234 terrace configuration and, to illustrate the effectiveness of this method, the model was returned to the T25x1 configuration, the least efficient configuration when different designs were tested in Section 8.2. In each subsystem five new outlets, each draining to an adjacent gully, were added at regular intervals. Table 8.5 compares applications with and without the 'safety valve' for the heavy storm and the extreme storm (the storms when such relief would be most applicable) on the T25x1234 configuration and the heavy storm on the T25x1 configuration.

Table 8.5 Comparison of Results for Terrace Systems Irrigation Outlet 'Safety Valve'

Event / Terrace	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)
Heavy Storm			
T25x1	15.9	483	590
T25x1 Gully	14.4	453	146
Heavy Storm			
T25x1234	11.6	330	54
T25x1234 Gully	8.0	179	n/a
Extreme Storm			
T25x1234	20.0	728	183
T25x1234 Gully	12.6	372	89

The results show marked improvements in terrace operation when excess water can be diverted into a nearby water course, even during the extreme event. On the T25x1234 configuration the impact of the heavy storm was reduced to approximately that of the standard storm of half the rain intensity. The impact of the extreme storm is also approximately halved, to around that the heavy storm, and brought within manageable bounds. Even on the least efficient system, T25x1, the impact of the heavy storm was much reduced. Although peak depth and outflow only reduced slightly, the time excess water remained in the system reduced to less than 25% of that of the previous application, from 590 minutes to 146 minutes.

The results illustrate that this type of terrace configuration is very efficient at shedding water during storms and, as this was tested on the most and least efficient terrace configuration, imply that this enhancement would be effective on all configurations of terrace systems. However, it would be problematic to deploy such configurations in the field. If extra outlets constructed to drain into gullies were permanently in use on terrace systems, the system would drain during inter-storm periods and the water balance would be lost. It may be possible for the farmer to open the five extra outlets only during storms or when they are imminent but this would be onerous and may be impractical. Alternatively, the mid-terrace outlets could be constructed with a higher clearance than the inter-terrace outlets so that they only come into operation when the depth of water in the terrace rose to a certain level, a universal standard in weir design in hydrological operations, so that draining only occurred during storms when excess water had reached a critical point.

However, no matter how it was implemented, the usefulness of this design is severely limited in practice because it could rarely be implemented in the field. Such configurations are only possible if there is somewhere adjacent to the terrace subsystem to which the water could be diverted. This might occur in situations where there is a neighbouring gully, more likely in terrace systems higher in the hillslope, as shown in Figure 3.2; or the khetland borders grassland or forest and the water can be channelled there. But as the photographs of khet hillslopes in Figures 3.1 and 3.4 indicate, this is almost never the case with the main systems. Where the farmer is lucky enough to be able to shed excess water in this manner, some kind of system to divert water may be present but mostly, once irrigation water has entered the system at the top terrace, there is nowhere for it to go except through the subsystem until it reaches the bottom terrace and exits to the irrigation system there.

This experiment was useful in that it did indicate the extent water needed to be shed from terrace subsystems to reasonably subdue system response to manageable proportions, if there was somewhere for the water to flow. In the case of the T25x1234 configuration when the heavy storm was applied this was 16.17 m^3.

8.6 Quantifying the Capability of the System to Lose Water via Irrigation Canals

Of more use and importance is quantifying the water exiting terrace subsystems from the lowest level, particularly quantifying how this is split between water being retained in the khet system, thus being channelled into the subsystem below as irrigation inflow; and water channelled away from the khet system completely, routed via irrigation canals into the hillside watercourses to become quickflow to the river. This facet of the system was modelled using both field and model data.

Field data for this experiment were provided by the results from one of the validation exercises described in Chapter 7. The model was validated on Khet PA when the Aug 3rd storm was modelled for 460 minutes (Section 7.7.4). In this application, modelling the reaction of Khet PA to the Aug 3rd storm was extended to 24 hours, which includes all the falling limb of the hydrographs, allowing the system to revert to its pre-storm position. The results of this application were analysed and the water exiting the lowest terrace in the system was divided into that channelled into the water courses and that made available to the khet subsystem immediately below. Using the same method of analysis, the standard and heavy storms were modelled on the T25x1234 terrace configuration and the split between water channelled into the water courses and that made available to the khet subsystem immediately below also calculated.

The storm of Aug 3rd comprised 45.8 mm of rain, all but 0.8mm falling in the first 5 hours. Irrigation input to the top of the subsystem during the 24 hours was 44.99 m^3. In addition to the field measurements reported, a further measurement of irrigation inflow was taken at 8:10am the following morning; field justification of the 24 hour figure for irrigation input was calculated from this using straight line averaging. The 24 hour model run predicted that total volume of water during this period over the outlets at the bottom of the system (ie. water exiting the system) was 88.40 m^3.

It is a reasonable assumption that terrace systems of similar characteristics react to rainfall in a similar way. As each terrace system receives approximately the same rainfall (per m^2) it is reasonable to speculate that the terrace system below Khet PA will react similarly to Khet PA. It is also reasonable to assume that the irrigation inflow to the terrace below Khet PA would be adjusted to be similar to that into Khet PA (otherwise the system would be overwhelmed) and that the maximum overall volume of water that the lower system could cope with is similar to the input of Khet PA. Once the maximum irrigation inflow to the next terrace subsystem has been reached, the excess must be channelled into the water courses to avoid the lower subsystem being overwhelmed. From the model application it is possible to estimate how much water was channelled by each route in the August 3rd storm.

From the figures provided by the 24 hour simulation, of the 88.40 $m^3$of outflow generated by Khet PA approximately 44.99 m^3 would be routed into the system below (equal to the irrigation input of Khet PA) so the remainder, 43.41 m^3, would be drained away by the irrigation canals, approximately 50% by each route.

The above analysis is from modelling field data from only one storm so the model was applied to simulate other situations to examine this facet in more depth. If there is an upper limit to the amount of irrigation water that can be absorbed by a terrace subsystem before it is overwhelmed, then when that limit has been reached the rest of the stormwater from any rain event must be channelled into watercourses. Model applications were undertaken on two identical khet subsystems, both with T25x1234 terrace configurations, the second subsystem being positioned on the hillside immediately below the original subsystem. The applications modelled 12 hours during and after storms of different intensity to try to quantify the percentage of water exiting the top subsystem channelled either to the one below or as quickflow (model applications of 12 hours rather than the 24 hours of field data modelling provided sufficient data for the analysis undertaken).

The original application of the heavy storm on the T25x1234 configuration resulted in a total 233 m^3 of water exiting the system from the four outlets in the bottom terrace during the storm and aftermath, until the pre-storm position was attained. If all this water was channelled to the subsystem below it would represent an irrigation rate of 303 l/min for the lower subsystem for the duration of the application. The work reported above suggests that not all the water could be absorbed by a second system as it would be overwhelmed. The model was applied to simulate reaction of the lower khet subsystem, during the same storm but with enhanced irrigation input to reflect the increase in irrigation rates that would be caused by the storm. Irrigation rates of 100 l/min, 150 l/min and 300 l/min were tested, representing irrigation input of 33%, 50% and 100% of the water exiting the higher system.

The model applications suggested that increased irrigation input would be contained in the top few terraces of the subsystem and made little difference to peak outflows at the bottom of the system but predicted terrace breakdown in the terraces part way down the system. This was because the increased irrigation inflow induced a wave of water in the subsystem, decreasing in peak depth but ‘spreading’, with increasing wavelength, as it progressed through the system. The sensitivity analysis in Chapter 5 concluded that the drivers of the storm reaction were increased rainfall coupled with consequent increased irrigation input. The applications here provide a more detailed example. The wave of water induced by irrigation inflow, lessening in effect as it progressed through the system, combined with the cumulative down terrace effect of rainwater, increasing in effect as it progressed through the system, and resulted in peak terrace depths in the system occurring between terrace 4 and terrace 7 (all four terraces having very similar maximum depth). The maximum depth recordings were 15 cms, 15.9 cms and 19 cms, for applications with irrigation rates of 100 l/min, 150 l/min and 300 l/min respectively. Table 8.6 gives maximum terrace depth for varying irrigation rates in the heavy storm; the final two rows show maximum terrace water depths for the standard and extreme storms at irrigation rates of 150 l/min, for comparison.

Table 8.6 Peak Terrace Depths at Varying Irrigation Rates

Storm	Irrigation Rate(l/min)	Peak Terrace Depth (cm)
Heavy	5	11.6
Heavy	100	15.0
Heavy	150	15.9
Heavy	300	18.9
Standard	150	10.3
Extreme	150	25.3

It is not possible to state precisely at what point a terrace subsystem would breakdown and these are speculative applications of the model but adding irrigation of 150 l/min to the rainwater input, inducing peak terrace depths of 15.9 cm, would possibly be the maximum the terrace subsystem could absorb and this value was selected for further experimentation. It should be noted that an irrigation rate of 100 l/min, inducing similar maximum depths of 15 cms, would also have been a valid selection and this is discussed below. An irrigation rate of 150 l/min is equivalent to half of the output of the terrace system in the heavy storm. So for a storm of this intensity the model predicts that a terrace subsystem of the T25x1234 configuration could absorb about 50% of the output from a similar terrace subsystem immediately higher on the hillside.

This is approximately the same proportion as that predicted by the application using field data from the August 3rd storm. However, this is just coincidence. Maximum irrigation rates are fixed, determined by the terrace architecture, and are unaffected by storm size. The ratio of the storm water exiting one system that is shed from the hillside as quickflow, compared to that which can be absorbed by the system below, must therefore increase at greater rainfall intensities (as one value is fixed, the other must increase).

Low intensity storms may be totally absorbed by the subsystem below; as storms increase in intensity the ratio channelled to quickflow will be higher and further modelling was undertaken to examine this ratio. Storms of different intensity were modelled for a 12 hour period on the pair of terrace subsystems described above, to calculate what percentage of outflow from the top terrace is absorbed by the second system and what percentage is channelled as quickflow, if an irrigation rate at the maximum of 150 l/min is assumed. From the subsequent results, quickflow was also calculated as a percentage of total rainfall. The results are presented in Table 8.7.

During the standard storm the second subsystem was able to absorb all of the increased output from the higher subsystem over the 12 hour period. As the standard storm is half the intensity of the heavy storm and the maximum irrigation rate was approximately half of the output of the heavy storm this is unsurprising. But maximum irrigation is only marginally greater than total outflow (115 m^3 compared to 111 m^3) so the model predicts that rainfall of this intensity can be regarded as close to the threshold at which quickflow is generated on khet terraces (this is not to suggest a threshold of quickflow generation on the hillslope, only a threshold within the khet system; quickflow will also be generated by other means, such as rain falling in gullies and on pathways).

Table 8.7 Proportion of Rainwater/Khet System Outflow Channelled as Quickflow

Total Rain (m^3)	Total Subsystem Outflow (m^3)	Maximum Irrigation to Next System (m^3)	Quickflow (m^3)	Quickflow % of Outflow	Quickflow % of Rainwater
150,000 (Standard)	111	115	0	0	0
200,000	186	115	71	37.8	35.1
250,000	235	115	120	50.8	47.8
300,000 (Heavy)	284	115	169	59.3	56.2
400,000	387	115	272	70.2	67.9
500,000	486	115	371	76.2	74.1
600,000 (Extreme)	585	115	470	80.3	78.3

As rainfall intensity is increased so does the absolute volume of quickflow generated, as would be expected. The results of these applications also show that the heavier the storm the greater the ratio of both rainfall and total outflow that is directed to the river as quickflow. Again, this makes sense intuitively. What is surprising is the prediction of the high proportion of the higher intensity storms becoming quickflow. When the standard storm increases in intensity by one third, increasing rainfall on the 100 m^2 khet subsystem from 150 m^3 to 200 m^3, the percentage of outflow and rainfall that become quickflow increases from zero to 38.7 % and 35.1 % respectively. Once the intensity of the standard storm has doubled to add 300 m^3 of water to the khet system, the proportions are 59.3% and 56.2%, respectively. For a very heavy monsoon storm, adding 600 m^3 to the terrace system, 80.3% of total outflow, representing 78.3% of rainfall, is channelled to the river. Effectively, the model predicts that very high proportions of high intensity storms are channelled to the river within twelve hours as quickflow.

The explanation for these extremely high ratios lies in the unique nature of khet systems. On almost all other land types quickflow generation ceases very quickly after rainfall ceases. On khetland, quickflow (or slightly delayed quickflow) continues for many hours after the cessation of rainfall. In fact, by the time the khet subsystem has returned to stability and its pre-storm position, all of the stormwater must have exited the lower terrace (apart from relatively small amounts lost to seepage and evapotranspiration) to be divided between irrigation to the next terrace subsystem or quickflow. Once the maximum rate of irrigation inflow has been reached, the rest of the storm must go to quickflow.

These figures may even be regarded as conservative, as very conservative values have been taken for both total outflow from the top system and maximum inflow possible to the second system. If the former increases or the latter is set at a lower value, each would increase the proportion of quickflow (because the maximum inflow is fixed). When running the model applications above to determine the split between irrigation and quickflow, the irrigation rate to the top subsystem was set to the default of 5 l/min, as it was for most model applications. This would only be true for the top terrace subsystem on the hillside, all others would have increased irrigation during a storm, in turn increasing eventual outflow. Therefore, in the above applications the total outflow from the top subsystem could be regarded as conservative as in most subsystems it would be higher that the figure reported here. Secondly, in the discussion above 150 l/min was taken as the maximum irrigation rate when modelling the point at which rainfall plus increased irrigation resulted in terrace breakdown. From the model results, a figure of 100 l/min could have just as legitimately been selected. Had that been the case, this would reduce the irrigation maximum and thus increase the ratio of total outflow from the top terrace that goes to quickflow.

Finally, a simple observation to support these high figures. If all terrace subsystems return to their pre-storm equilibrium position, i.e. the same water volume and depth, within 12 hours of the cessation of rain; apart from small losses to seepage and evapotranspiration, all of the storm water that fell into the khet systems must after 12 hours have been diverted to the river as (delayed) quickflow. There is no other feasible mechanism to divert it elsewhere.

8.7 Modelling Terrace Reaction to Variations in the Frequency of Rainstorms

Previous sections of this chapter have examined varying terrace reaction to rainstorms of different intensity (the standard, heavy, and extreme storms). This section considers terrace reaction to variations in storm frequency (more specifically, increased frequency; Section 8.4 looked at the buffering capacity of terraces when frequency was low). If the frequency of storms is such that a second or subsequent storm arrives before all the water from the initial storm has cleared the system, system reaction to the storms that follow will be reinforced by the antecedent position of the terraces. This section speculates as to the reaction of khet systems over longer time frames when further storms are applied to the model, with different frequency and magnitude.

Previous tests have used the time a terrace system takes to return to the pre-storm equilibrium as one basis for comparison of terrace reaction to different storms. If a second storm occurs before the pre-storm equilibrium is regained, the reaction to the second storm will be reinforced by the initial storm. Table 8.8 reproduces the time to pre-storm stability of the bottom terrace in the T25x1234 terrace configuration in the standard, heavy, and extreme storms.

Table 8.8 Time to Regain Pre-Storm Stability

	Time (mins)
Bottom Terrace - Standard Storm:	601
Bottom Terrace - Heavy Storm:	619
Bottom Terrace - Extreme Storm:	651

The time to stability of the bottom terrace obviously represents the time to stability of the whole system. Figure 8.1 illustrates, showing the hydrographs of draining from the bottom terrace for the three storms.

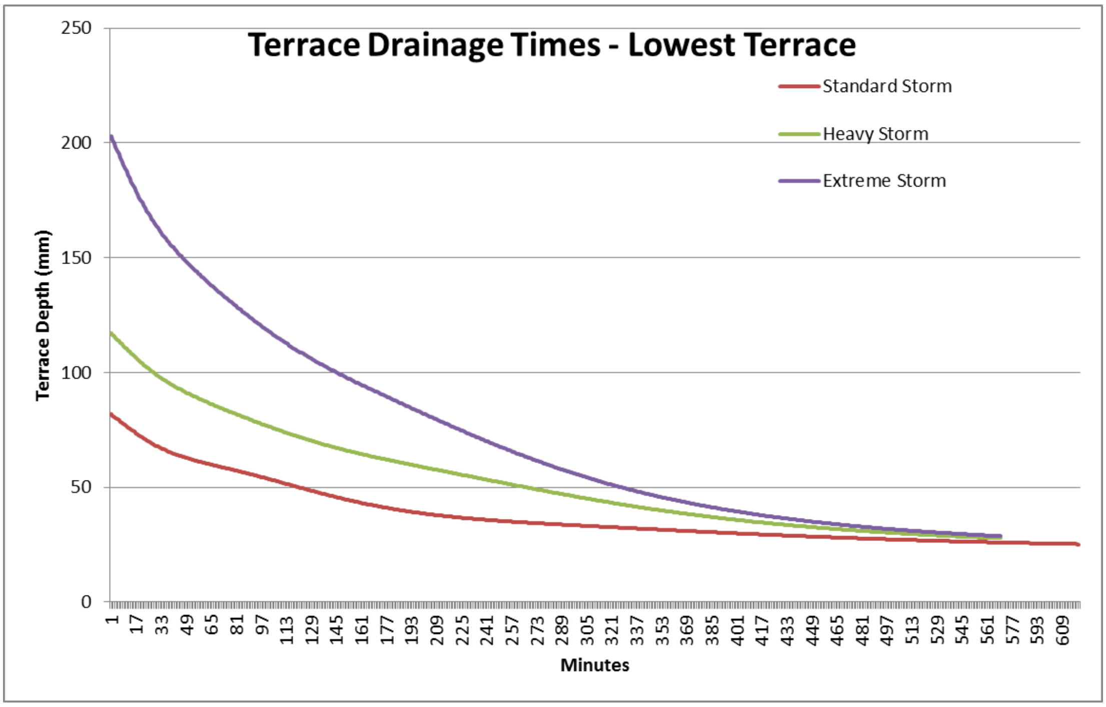


Figure 8.1 Bottom Terrace Drainage Times for the three test storms.

Analysis of these drainage patterns allowed several points to be made:

1. Storm intensity has low impact with regard to total drainage times. The extreme storm had four times the intensity of the standard storm but only took an extra 50 minutes to clear the system.

2. The hydrographs have a negative non-linear component, (as was shown in the sensitivity analysis in Chapter 5) which results in peak terrace depths falling rapidly initially and the hydrograph having a long tail. Chapter 5 demonstrated this shape of graph for the top terrace but the same characteristics are seen in the bottom terrace, even though this terrace is being continually replenished from the terraces above. All three storms took more than 10 hours to clear the system completely. However, 50% of the water was drained from the bottom terrace in only 98 minutes, 124 minutes, and 110 minutes for the standard, heavy, and extreme storms, respectively. So even though excess water remained in the system for more than 10 hours, it is likely that through much of

the latter part of this period there would be little reinforcement of the impact of a second storm, but dependent on timing.

3. The lowest terrace, as would be expected, has the longest time to return to pre-storm stability and represents the time taken for water to clear the whole system. Terraces higher in the system will clear excess water quicker, the top terrace will clear quickest and the time taken to clear will grade from top terrace to the bottom terrace; for example, 150 minutes to 619 for the top and bottom terrace in the heavy storm. As with the previous point, even though excess water remained in the whole of the system for more than 10 hours, it is likely that through much of the latter part of this period there would be little reinforcement of the impact of a second storm because higher terraces had already drained to pre-storm levels. The extent of this is again dependent on timing.

4. Most importantly, the terrace systems are very efficient at draining excess water and a second storm would have to follow very closely behind the first for the terrace system to retain sufficient water for the first storm to have a significant impact. This is discussed below in a worst case scenario when there is constant rainfall which, if continuing for sufficient time, can be considered as several consecutive storms with no time interval between each.

Further modelling is required to examine the implications of the above points but selecting storm sizes and frequencies that are reasonable and representative is problematic. In the situation being modelled, storms of different intensity over longer timeframes, many variations are possible and the legitimate range of possible modelling scenarios is huge. When considering khet system reaction over several days, if the standard storm was applied to the terrace system once every 24 hours, the data above show that the antecedent terrace position would be irrelevant, as the system only takes 601 minutes to drain the excess water, and the result of modelling this longer period would simply be cyclic replications of the standard storm. On the other hand, if a second extreme storm was applied two hours after a first had ceased, the antecedent position would obviously have impact.

Rainfall records from the Likhu Khola valley and the Modi Khola valley (discussed in Section 3.7) indicate that 2,800 mm and 6,000 mm, respectively, are typical annual rainfall totals; the Modi Khola catchment, draining from the Annapurna range, having one of the heaviest monsoon rainfall totals in Nepal. If the total annual rain falls in the 120 day period representing the monsoon, including pre and post monsoon rains (which is not the case, particularly in the Modi Khola), then this represents daily rain of only 20.8 mm and 50 mm respectively. This can be compared to the standard storm, which consisted of 60 mm of rain.

For the purpose of illustration, several extreme storm situations were modelled to show that the antecedent position of terraces probably has little importance. Three 24 hour storms were applied to the terrace system, at intensities of 30 mm per hour, 45 per hour, and 60 mm per hour respectively, all on the T25x1234 terrace configuration. These represent rainfall totals of 720 mm, 1080 mm, and 1440 mm in 24 hours. Lower rainfall intensities than in previous modelling are justified by keeping the total rainfall within the bounds of reality though, even at lower intensity, storms of this magnitude are stretching credulity. The 1440 mm storm is equivalent to 24 consecutive standard storms or 12 consecutive heavy storms, without respite. Twenty four hour storms do occur but it is difficult to imagine such intensity levels being maintained for that period as storms of this size would represent 28.8%, 43.2%, and 57.6% of the typical annual rainfall in the Likhu Khola and 12%, 18%, and 24% of the typical annual rainfall in the ModiKhola.

Following this, as a final test the heavy storm was modelled on the T25x1234 configuration, followed by a second storm or the same intensity four hours after the first had ceased.

Applying continuous rainfall results in the system stabilising at a new higher equilibrium, as inputs and outputs are all constant. When 30 mm of rain was applied continuously, the system stabilised with only 11.1 mm of water depth in the bottom terrace. For continuous rain of 45 mm per hour the peak depth of the bottom terrace stabilised at 14.6 mm. It is only when continuous rain of 60 mm per hour is applied (an unlikely total of 1440 mm of rain in 24 hours) that the bottom terrace stabilises at a probably unmanageable 17.9 mm depth. If continuous rain at unrealistic magnitude does not cause breakdown, it is difficult to imagine antecedent conditions having a great impact, especially when water levels are quickly falling during inter-storm periods.

This conclusion was supported by the results of the model application whereby a second heavy storm was applied only four hours after the first had ceased. The impact of the antecedent position was negligible. Table 8.9 compares the impact of the second storm to that of the initial storm and shows that by the end of the second storm the additional reaction generated by the antecedent position only increased peak depth by 0.8 mm, peak outflow by 34 l/min, and the time excess water remained in the system by 32minutes. The time taken to retain stability increased by 62 minutes, an approximate 10% increase but, because of the long hydrograph tail, all of this additional time represented the draining of the last 2 mm.

Table 8.9 Terrace Reaction to Two Heavy Storms in Close Proximity

Event	Peak Depth (cms)	Peak Outflow (l/min)	Depth > 10cms (mins)	Stability (mins)
First Heavy Storm	11.6	330	54	619
Second Heavy Storm	12.4	364	86	682

The question being considered during these applications was at what point antecedent conditions become important. The modelling of these extreme situations suggests that the threshold of this is very high and that situations in which antecedent conditions have significant impact are likely to occur very rarely.

8.8 Research Summary

Chapters 1 and 2 of this thesis introduced the research and the context in which it was undertaken, explaining that during the last 60 years or so Nepal has been subject to rapid population growth which has placed pressure on the physical environment. Many of the consequences have been adverse, though the severity of those consequences has been subject to much debate. Further research by two DfID funded projects in the 1990s provided greater understanding and concluded that land degradation in general and soil erosion and landsliding in particular were not major problems in Nepal (Gardner and Jenkins, 1995; Gardner et al., 2000). Gardner and Jenkins (1995) also speculated that conversion of land to khet use may be beneficial if it restricts quickflow and thus reduces the propensity for flooding, leading to higher base flow and increased irrigation water availability in the dry season. The aim of the research presented here was to better understand the surface hydrology of khet systems to test this hypothesis.

The highly structured nature of the khet environment advocated the deployment of a computer model as the most appropriate method of fulfilling the research aims, particularly as it was possible to collect specific empirical data for calibration and validation. The KhetFlow model was conceived and developed in line with the 'funnelling' process advocated by Beven (2012). Perceptions gained from general observations, the development of a prototype model, a pilot study in Nepal and subsequent extended fieldwork provided insights. Most importantly, that rainfall and irrigation increase (of which rainfall is the main component) seemed to be the drivers of the system and overwhelmed other processes; that khet hillslopes are divided into subsystems; and that the interaction between terraces in the subsystems and between the subsystems themselves are as important as the reaction of a single terrace to storms. The importance of keeping process rates within a narrow range and maintaining a water balance within khet subsystems was also suggested.

Chapter 2 described the perceptions and explained how those evolved into a conceptual model, considering the water stores in khet systems, the transfers between them and how each could be quantified, before specifying the procedural model that was subsequently developed to conduct the remainder of the research. Chapter 3 explained why the distribution of khet terrace subsystems on the hillside and the interaction between these also had to be explained to give the hillside context, if the systems in which the model was deployed were to be fully understood.

In one of the most important chapters of this thesis the sensitivity of the system was investigated in Chapter 5, which provided model confirmation of perceptions discussed in Chapter 2. Initial sensitivity tests considered a single terrace in isolation and concluded that when variables are set within acceptable ranges and situations are tested that realistically reflect field conditions the most important variable acting on the khet system is rainfall intensity, particularly when coupled with irrigation inflow, of which it is the main component during a storm. However, sensitivity tests on multi-terrace systems showed that overriding this was the need to maintain a water balance in the system and that multi-terrace systems will only function successfully within a narrow range of process variables. If the model was to be a viable representation of reality, this requirement represented the most important control.

Chapter 6 described the calibration of the model and fulfilled two important functions. Firstly to estimate net loss from evaporation, seepage and return flow (within the bounds of acceptable field values) and secondly to demonstrate that the KhetFlow predicted the surface hydrological response of khet systems to storms with reasonable accuracy (i.e. that the model worked). Five of the six events monitored provided acceptable replications of field values, many of the model predictions being within +/- 5mm of the field data. The mean net loss figure for those five events, 73 ml/m^2/min, was then utilised in the validation exercise, described in Chapter7.

Model predictions of the four events used for validation were not as accurate as those for calibration but most individual terrace events were still predicted with acceptable accuracy, to within +/- 1cm of field recordings. It was concluded that many of the inaccuracies were a probably introduced by the problems faced collecting field data in adverse conditions.

The aim of this research was to develop and deploy a computer model to provide greater understanding of the surface hydrological response of khet terrace systems to monsoon storms at the hillslope scale. This was achieved, as were the following specific objectives stated in Section 1.5:

1. To conceive, develop and test a computer model to replicate, through the use of mathematical algorithms, the flow of water through khet terrace systems.

2. To undertake extensive field studies on khet systems in The Middle Hills of Nepal during monsoon storms to gather data on surface hydrological processes with which to calibrate and validate the model.

3. From these field data and the modelling of khet systems, to ascertain the dominant variables and processes controlling the surface hydrology of khet terraces.

4. To determine the volume and timing of water held in temporary storage in khet terraces and understand the mechanism by which it is released to the main river system, using the field data and the Khetflow model.

The additional objective of developing a model to reliably replicate processes from as few, preferably easily measured, variables as possible was also successful.

The overall aim of this research and the final specific objective listed in Section 1.5 were “to better understand the surface hydrology of khet systems to allow predictions of khet system response to storms at the hillslope scale”. To this end, in Chapter 8 the

KhetFlow model was deployed in predictive situations as reported above and the conclusions of that are presented in the section following.

8.9 Research Conclusions

As has been stated throughout this research, khet subsystems need to be constructed with dimensions that allow a water balance to be maintained within the system in order to provide a ponded environment for rice to flourish. Subsystems need to preserve such a balance when the water supply is solely irrigation inflow, and when the water supply is a combination of irrigation inflow and rainfall. The design of the system must also be able to absorb rainfall typical of monsoon conditions largely without break down and overflow. In Section 8.2 different terrace configurations were modelled in order to test which successfully replicated this basic control, to provide a structure for further experimentation. Of the six systems tested, the configuration with one outflow per terrace in the top terraces of the system, augmenting to four outflows per terrace in the lower terraces, was the most efficient at maintaining a water balance and absorbing the heavier storms. In principle, this matched field practice, where it is normal for terraces lower in the system to have more outlets in order to manage water accumulation. This configuration, designated T25x1234, was then utilised for further modelling experimentation.

Section 8.3 considered the strategy for further experimentation in the light of the control imposed by the need to maintain water balance, which was important if insight as to the surface hydrology of khet hillsides in monsoon storms was to be gained in a pragmatic manner compatible with farming practice. Scenarios investigating changes in terrace area and connectively, the number of terrace drops, lateral transfer between terraces at the same elevation, manual draining of terraces during storms and any factorial combination of these were considered but not tested because they were either impractical in the field or they would impact on the water balance and render the systems inoperable. Further experimentation was then concentrated in four areas:

- Quantifying the Buffering Capacity of Drained Terrace Systems to Storms (Section 8.4)
- Quantifying the Capability of the System to Lose Water via Adjacent Water Courses (Section 8.5)
- Quantifying the Capability of the System to Lose Water via Irrigation Canals (Section 8.6)
- Modelling Terrace Reaction to Variations in the Frequency of Rainstorms (Section 8.7)

These tests reflected field circumstances and highlighted the situations of most interest and concern during monsoon storms on khet hillside. They also tested and identified important thresholds in the operation of khet systems.

Several conclusions were drawn from the results of this model experimentation (it should be emphasised that these are conclusions drawn from model predictions, not empirical data):

1. Terrace systems, once balanced to operate correctly, are very efficient on the one hand at attaining a ponded balance and on the other at shedding excess water during and after storms.

2. Experiments to test the buffering capacity of drained terraces showed that this was limited. Ponding and 'normal' flow was quickly regained after the onset of rain, with limited overall mitigation of storms.

3. Experiments to test the consequences of second or subsequent storms following quickly after the cessation of initial rain showed that in almost all cases the antecedent position caused by the initial storm effected little change in system reaction to the second storm, as khet systems drain water relatively quickly.

4. Draining terrace systems from outlets at mid-points in the subsystems was seen to be a very effective method of preventing terrace breakdown in heavier storms but this has limited practical use as there is usually nowhere suitable for the water to drain.

5. Very high levels of quickflow generation were predicted, particularly during heavier storms.

The final point was the main concern highlighted by model experimentation. Fieldwork in Nepal and interviews with farmers had determined that irrigation canals had the secondary, important function of draining excess water away from the khet systems, to prevent overflow and breakdown. Ideally, canals would be positioned after every 10 to 30 'drops' of the terrace system. Experimentation with two khet subsystems, each of 25 drops and aligned vertically on the hillside, suggested that once the threshold of maximum irrigation inflow had been reached in the lower system, further rainfall had to be channelled into the catchment watercourses as quickflow. The model predicted that modest storms would be absorbed by the terraces but because the unique character of khet systems allowed quickflow to be generated for many hours after rain stopped, heavier storms were problematic. As storm intensity increased, the model predicted that 50% and more of storm water eventually drained to the river, perhaps not as quickflow in the traditional sense but as 'delayed quickflow'. Certainly, the water is not retained as baseflow.

It is perhaps interesting to consider the scale of quickflow generation predicted here with values for surface runoff generation on other land types, especially in Nepal. Runoff generation was recorded for other land uses during various stages of the overall programme of research in Nepal. The figures reported are in most cases seasonal totals of runoff from experimental plots and so are not like for like comparisons, but they serve to illustrate the scale of the difference. Gardner and Jenkins (1995) measured less than 1% runoff from forests, 0.5% to 2% for grassland and 3% to 26% for bariland in the Lhiku valley. Gardner et al. (2000) also recorded 1% to 18% runoff from bariland in three different regions of western Nepal; Acharya et al.

(2007) reported levels ranging from 4% to 12% from bariland under various test crops in a high rainfall area and Acharya et al. (2008) report estimates of 2% to 9% from the larger bari terraces in Palpa district. The only figures of the magnitude of those predicted by the model for khet systems were of 5% to 64% runoff from degraded forest and 18% to 57% runoff from bari terraces with particularly erosion prone soils, both in the Likhu valley (Gardner and Jenkins, 1995). Runoff coefficients used in Rational Method formulas only approach the values predicted for these khet systems when calculating runoff from various forms of semi-impervious developed land (McCuen, 1998).

Whilst these comparisons should be interpreted with much caution, the indication of enhanced runoff from khetland is of considerable importance when viewed in the context of the conversion of other land types to khet. In the setting of The Middle Hills of Nepal, this would increase the erosive power of smaller streams and contribute to excessive gullying; and reduce baseflow and thus water availability when it is most needed during the dry season. If land conversion increases the quickflow component of rivers, albeit delayed for many hours (which may reinforce or attenuate reaction, dependent on timing and position in the catchment) greater propensity for flooding is introduced. A conservative interpretation of these figures is that the model indicates conversion of forest or grassland to khet would increase surface runoff considerably and that runoff from khet systems is even greater than that of the possible high values from some bari terracing. It should also be remembered that bari terraces were once forest or grassland and if they ultimately become khet, as has been the trend in the Middle Hills, in this sense their function as bari terraces can be regarded as a temporary stage between conversion from forest or grass to khet.

Gardner and Jenkins (1995) provided the working hypothesis at the start of this research “The routing of water through the canal system and the khetland, will introduce a substantial delay into the natural hydrological system in areas where the proportion of khetland is high. This will lower the potentially high peak discharges during heavy storm events”. The conclusion of this research is that, based on the model predictions, this is not the case. Indeed, the results of modelling suggest that the opposite is probably true.

If one of the main purposes of modelling is to provoke insight, then the simple observation that if terrace subsystems regain the pre-storm position within 12 hours of the storm ending, as empirical data and the model predictions suggest, then most of the storm water, apart from small losses to seepage and evapotranspiration, must be diverted to the catchment river as (delayed) quickflow; is the insight gained by this research.

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Appendix A1: Hydrographs of Optimum Calibration Events

A1.1 July 11th Event

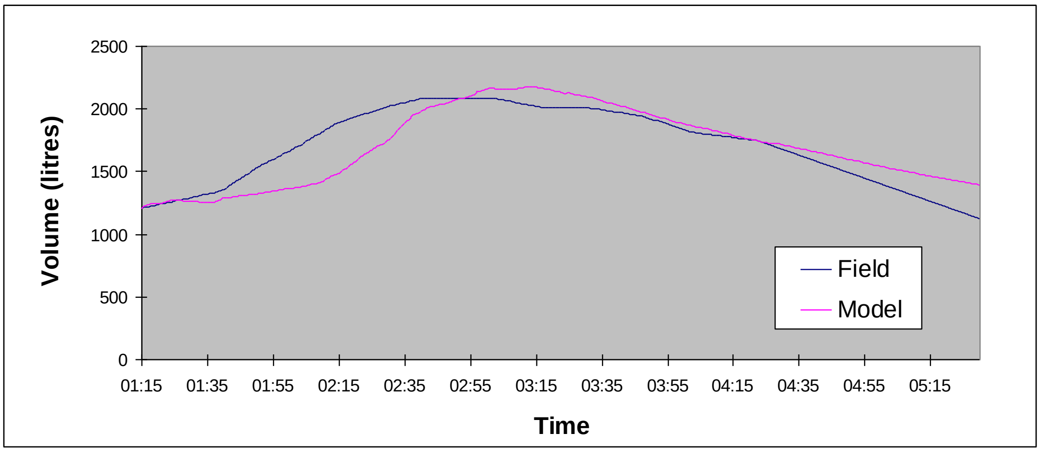


Figure A1.1a July11-14 Terrace HA1 Water Volume

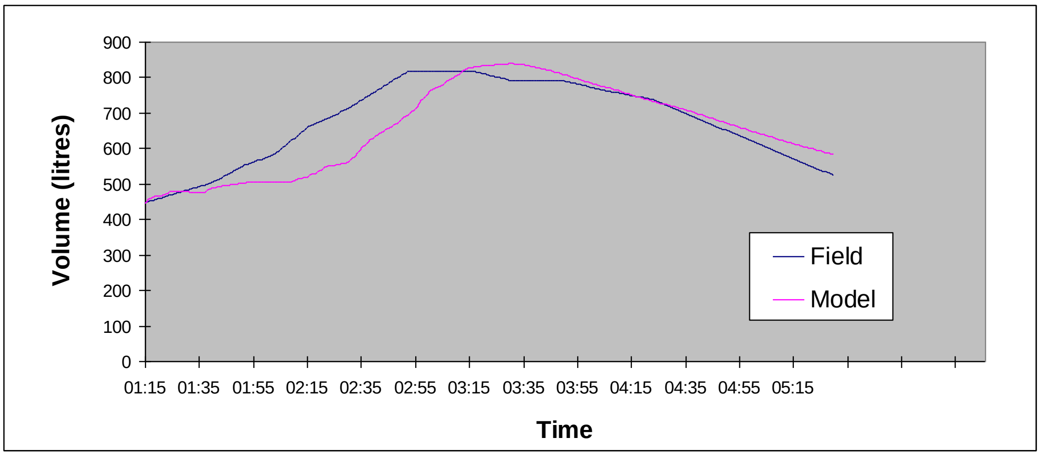


Figure A1.1b July11-14 Terrace HA2 Water Volume

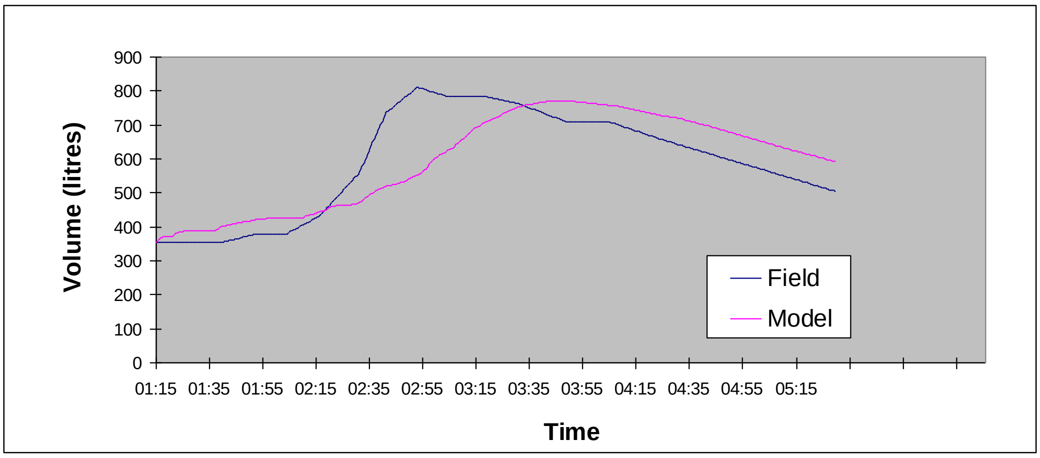


Figure A1.1c July11-14 Terrace HA3 Water Volume

A1.2 July 13th Event

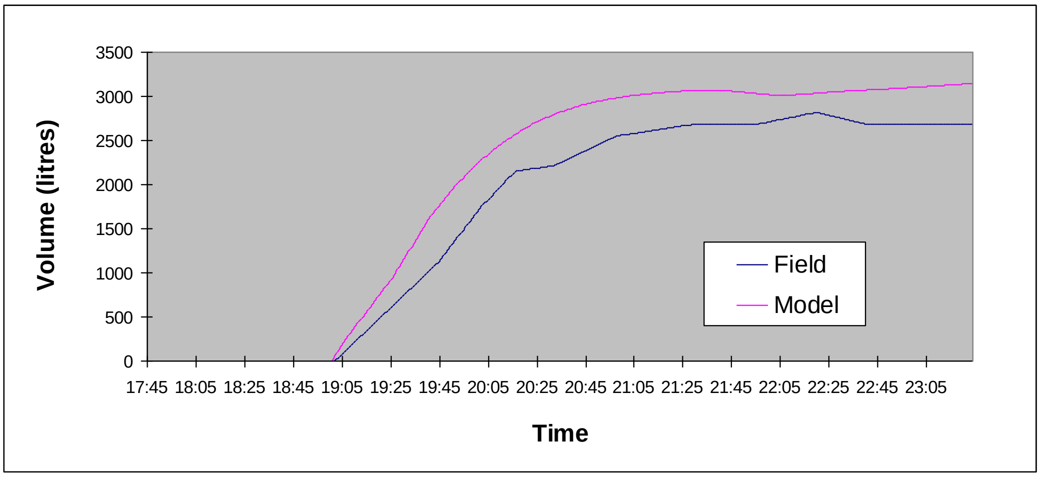
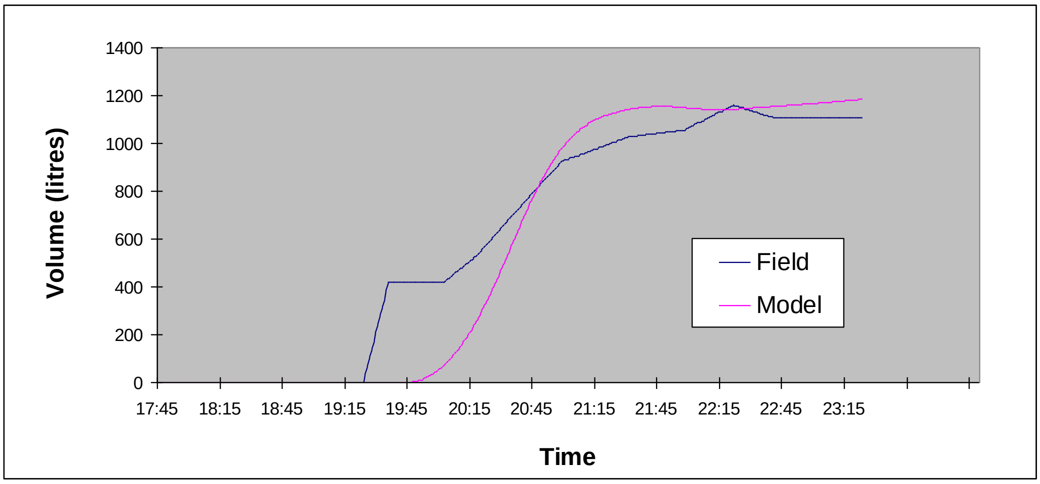


Figure A1.2a July13-141 Terrace HA1 Water Volume



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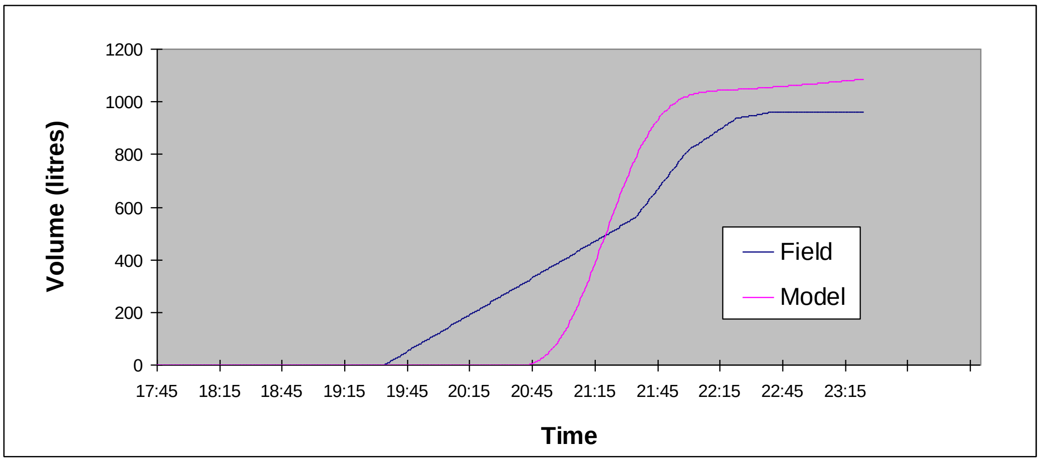

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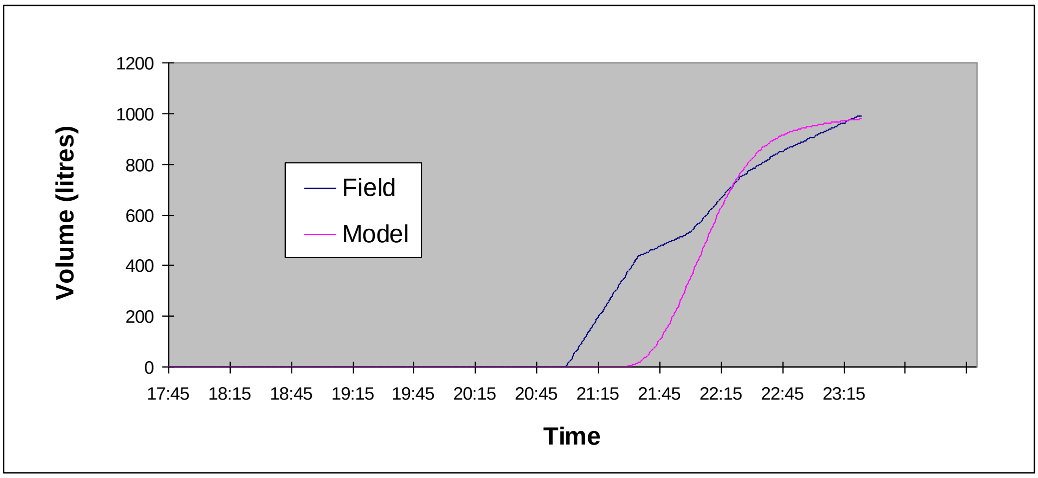

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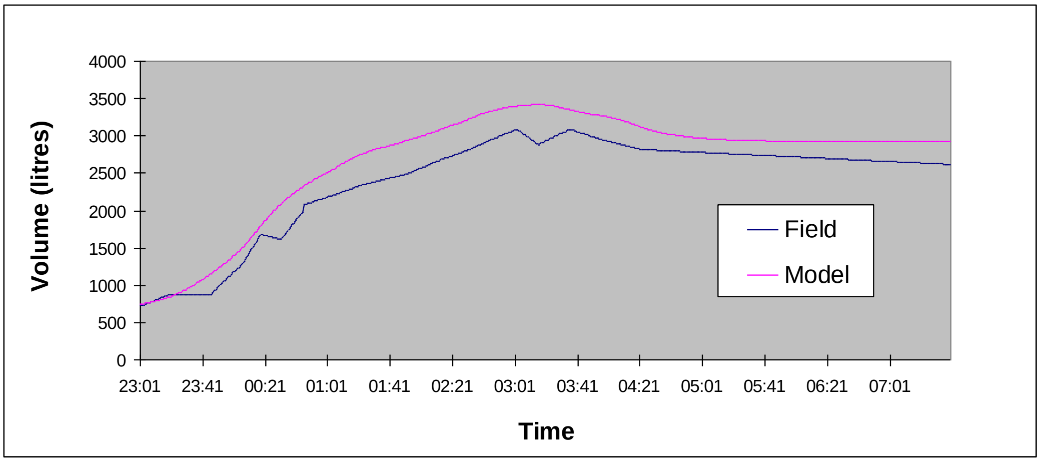

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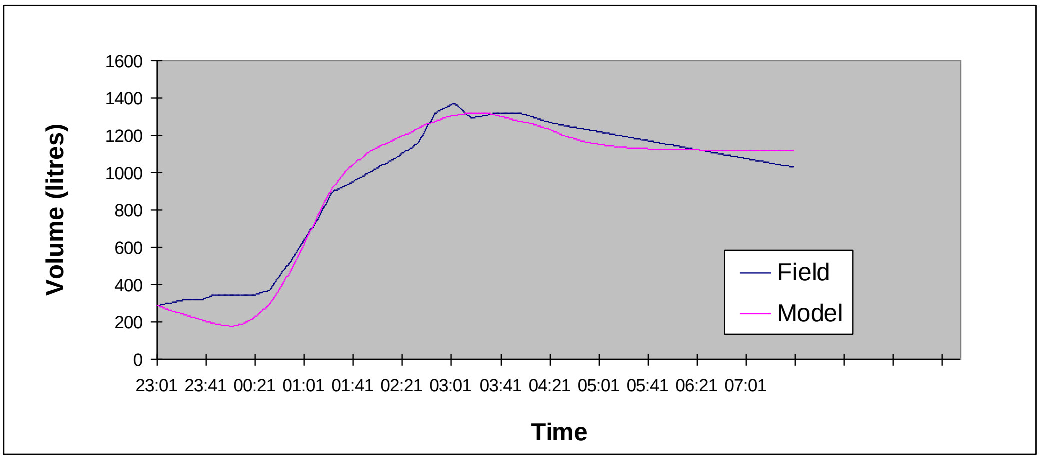


Figure A1.3b Jul16-107 Terrace HA2 Water Volume

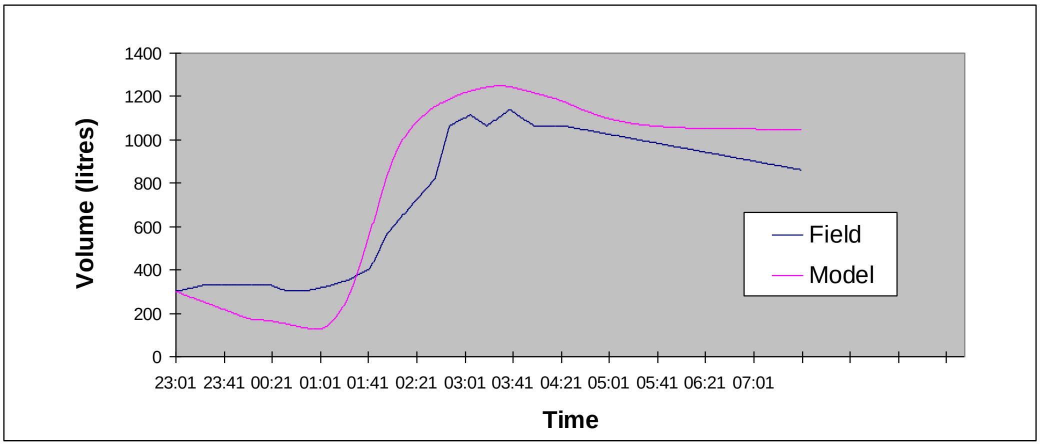


Figure A1.3c Jul16-107 Terrace HA3 Water Volume

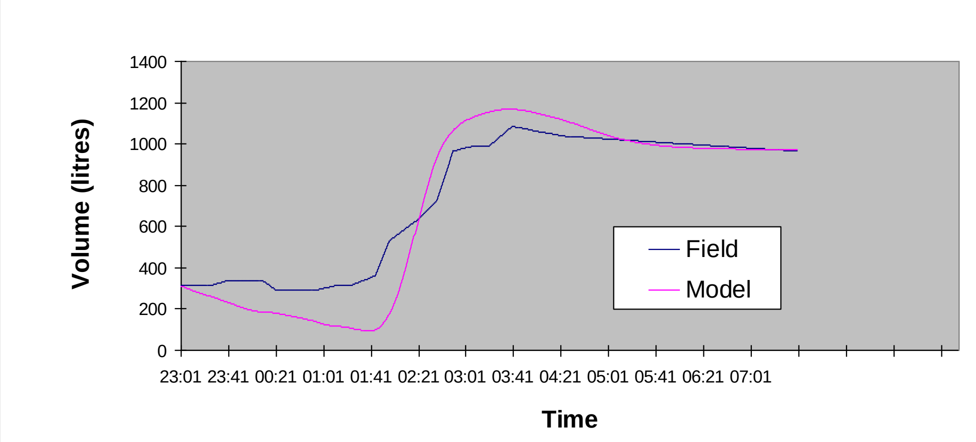


Figure A1.3d Jul16-107 Terrace HA4 Water Volume

A1.4 July 17th Event

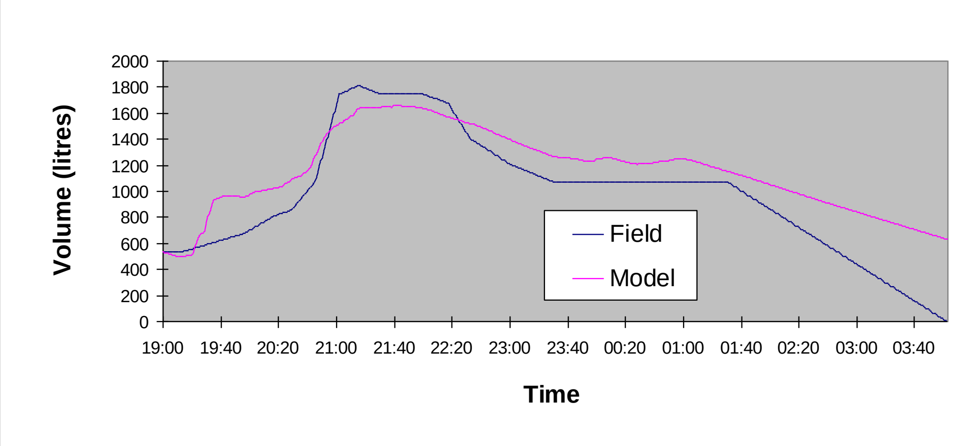


Figure A1.4a Jul17-107 Terrace HA1 Water Volume

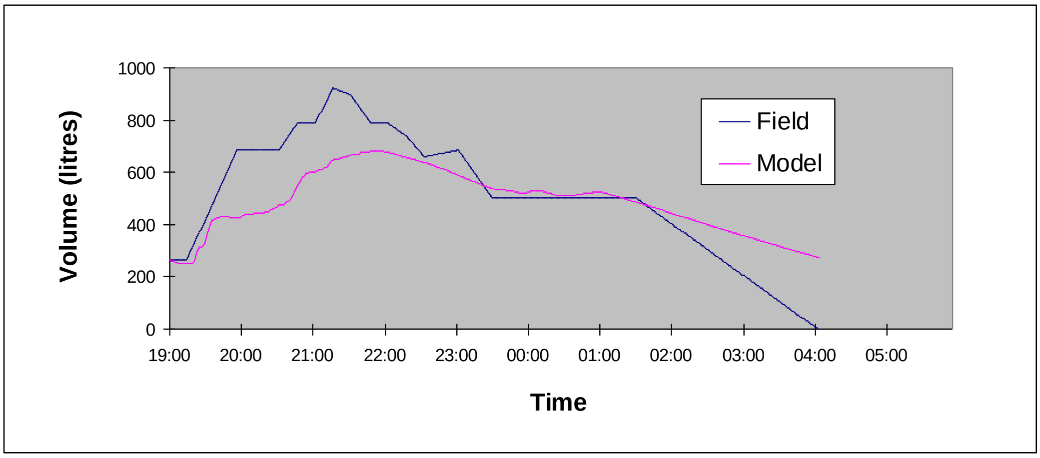


Figure A1.4b Jul17-107 Terrace HA2 Water Volume

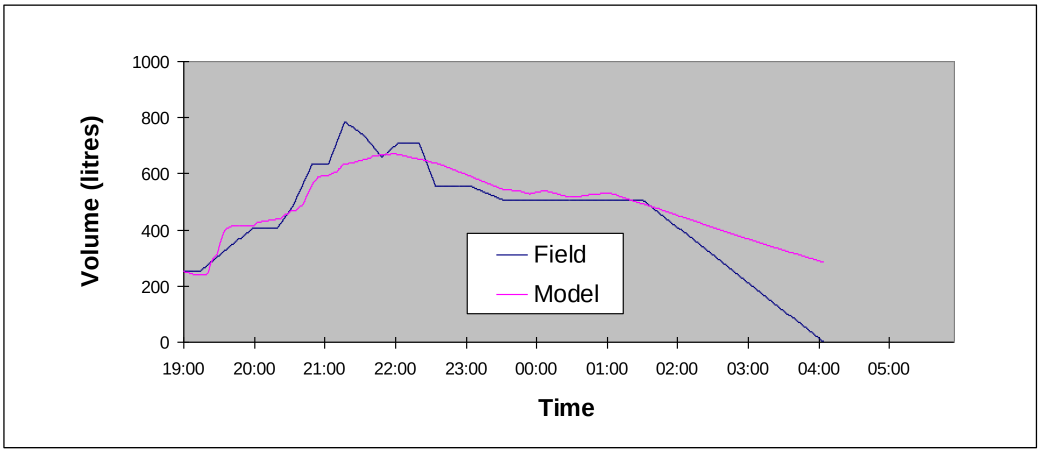


Figure A1.4c Jul17-107 Terrace HA3 Water Volume

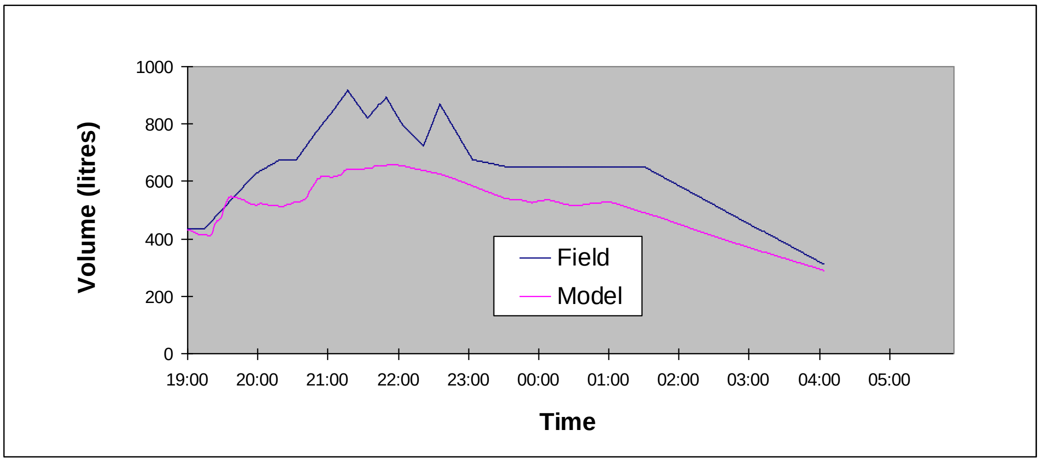


Figure A1.4d Jul17-107 Terrace HA4 Water Volume

A1.5 July 30th Event

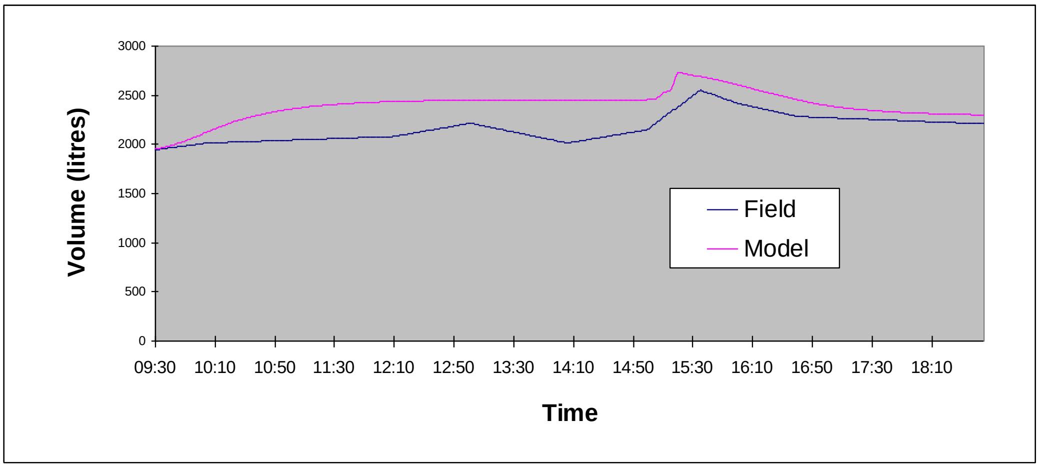


Figure A1.5a Jul30-107 Terrace HA1 Water Volume

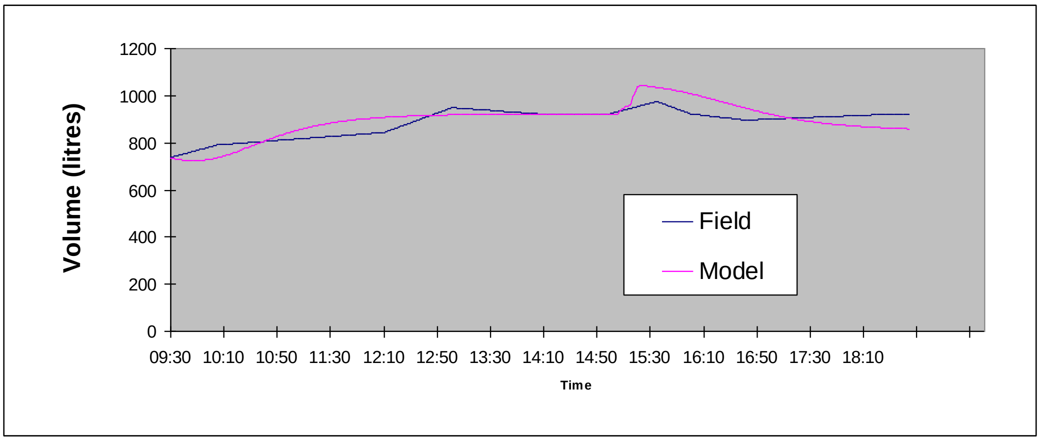


Figure A1.5b Jul30-107 Terrace HA2 Water Volume

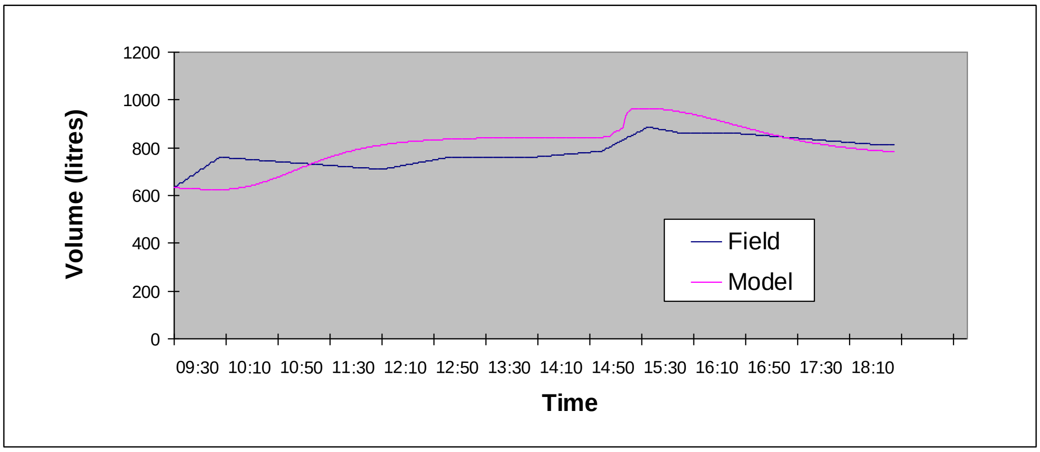
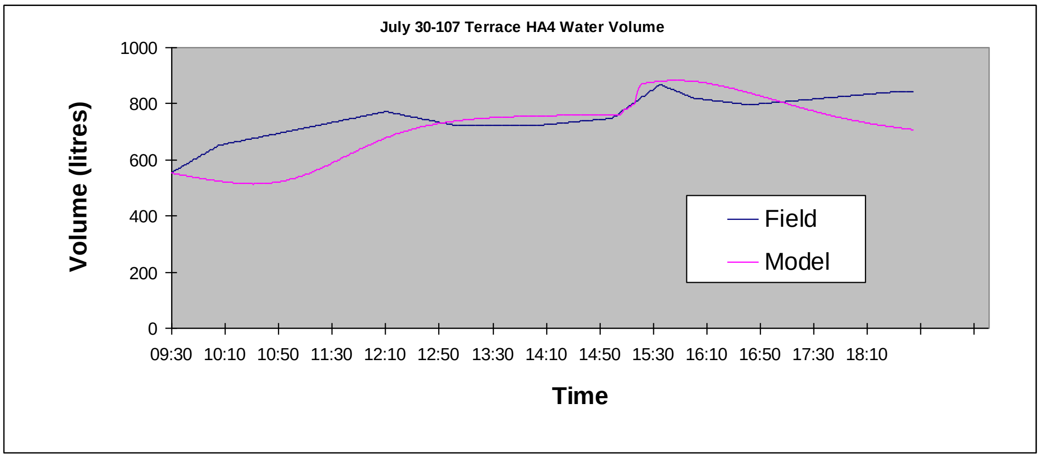


Figure A1.5c Jul30-107 Terrace HA3 Water Volume



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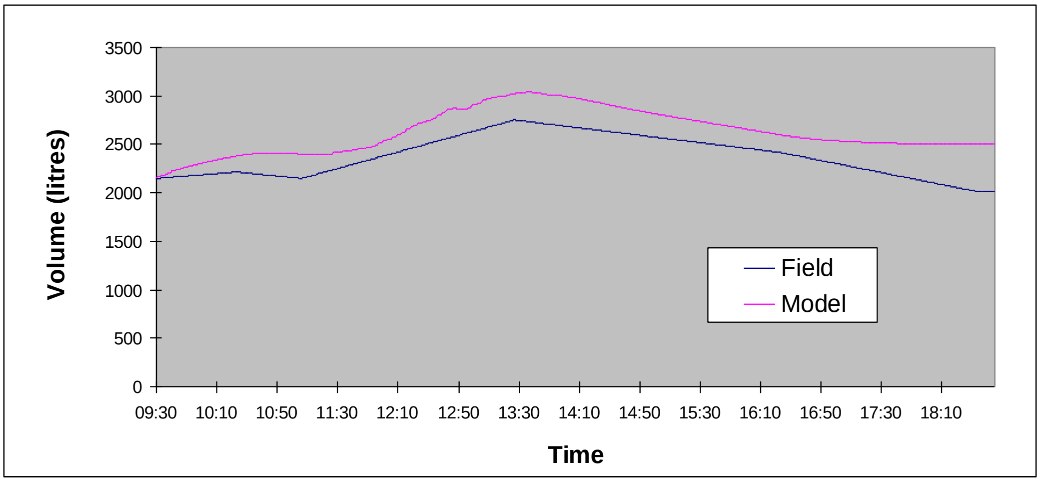
A1.6 July 31st Event



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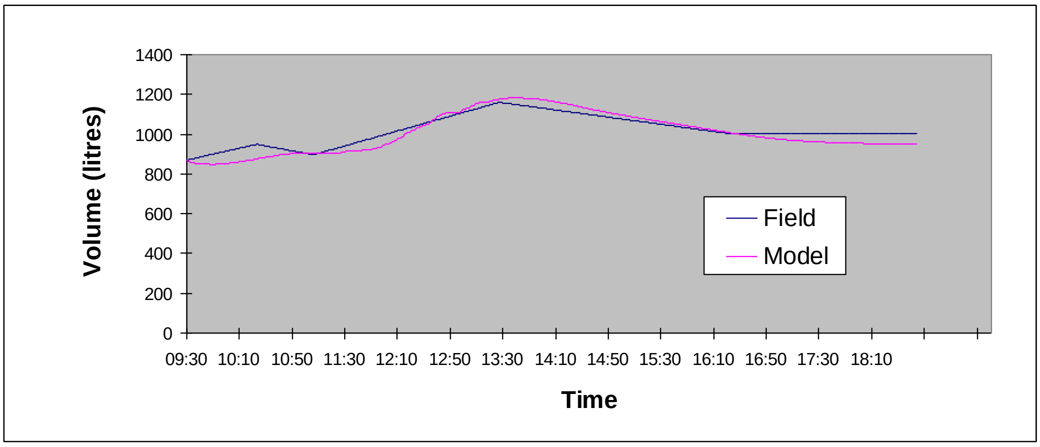

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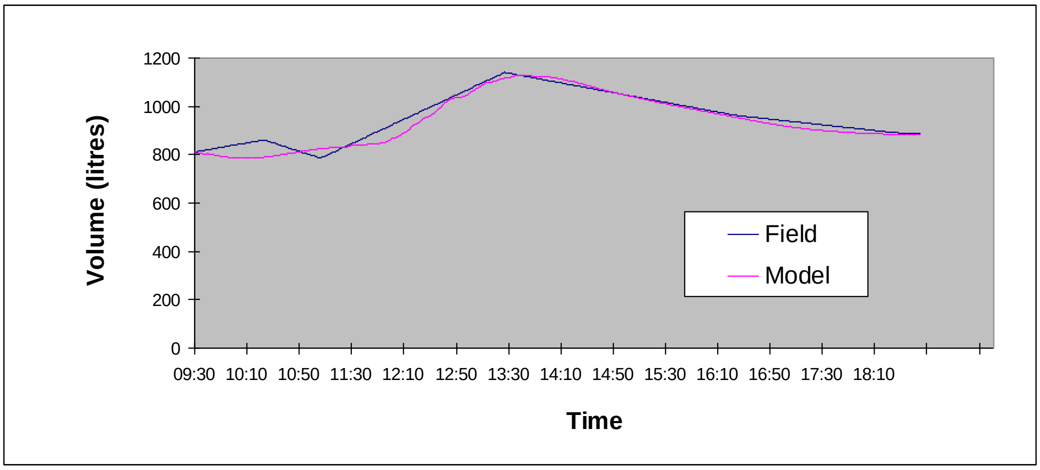

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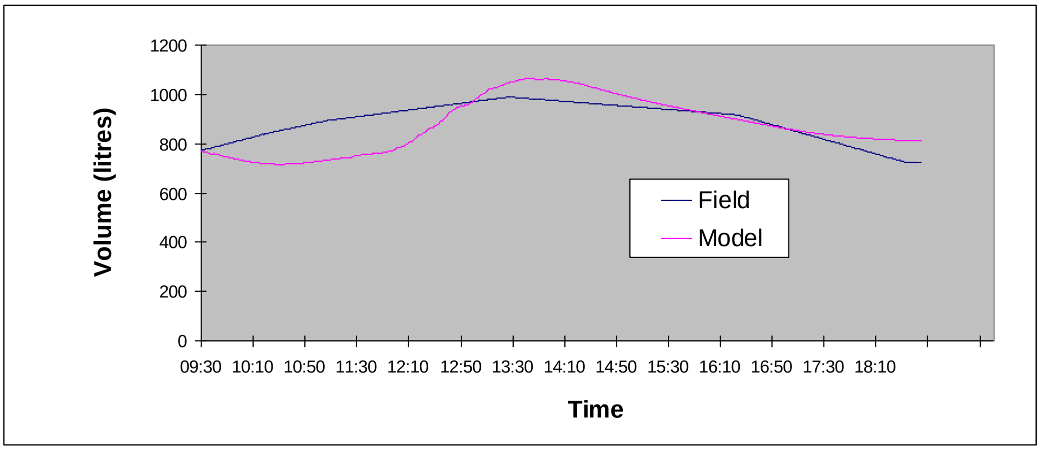

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Appendix A2 – Hydrographs of Validation Events

A2.1 July 17th Event – Khet HB

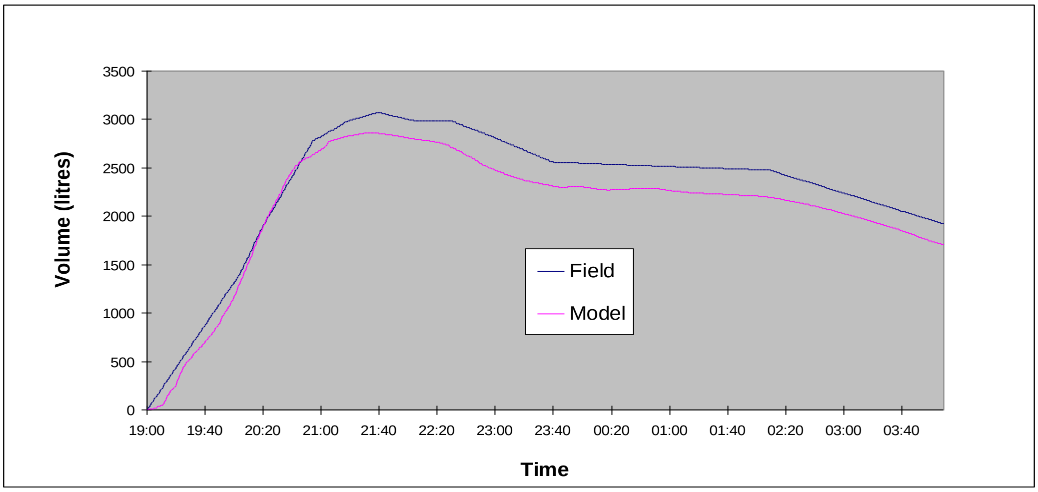
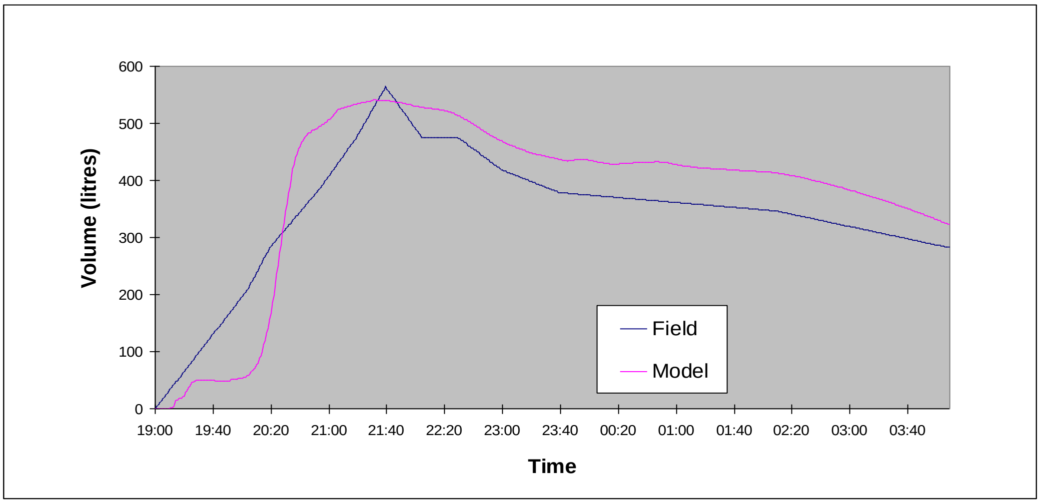


Figure A2.1a July17 Terrace HB1 Water Volume



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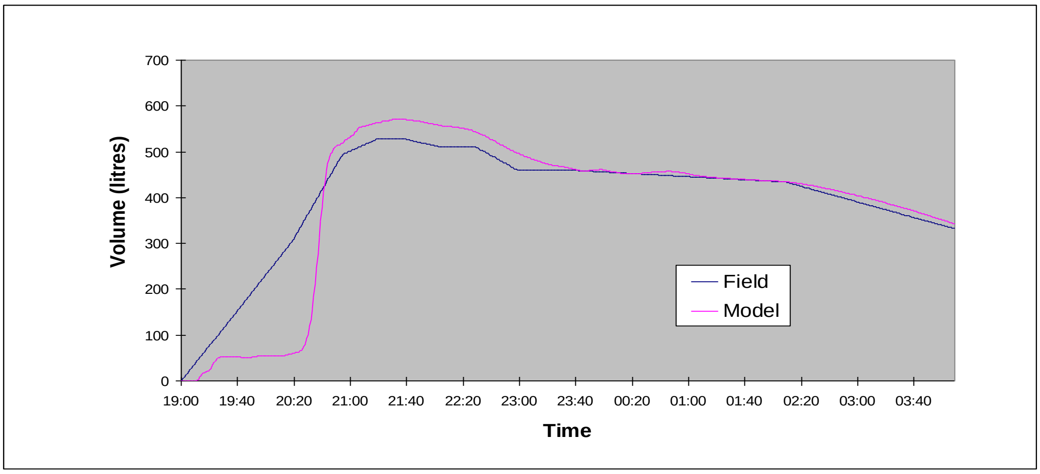

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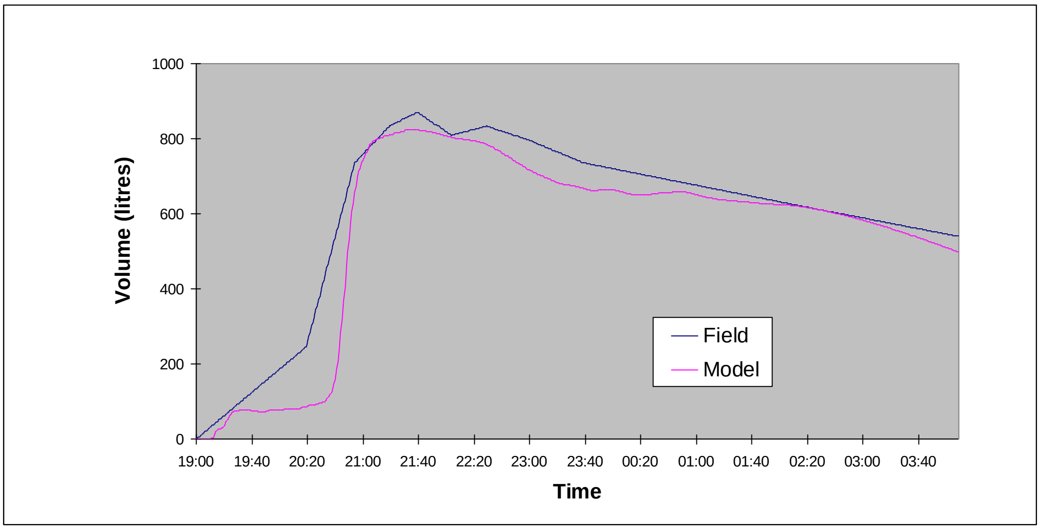


Figure A2.1d July17 Terrace HB4 Water Volume

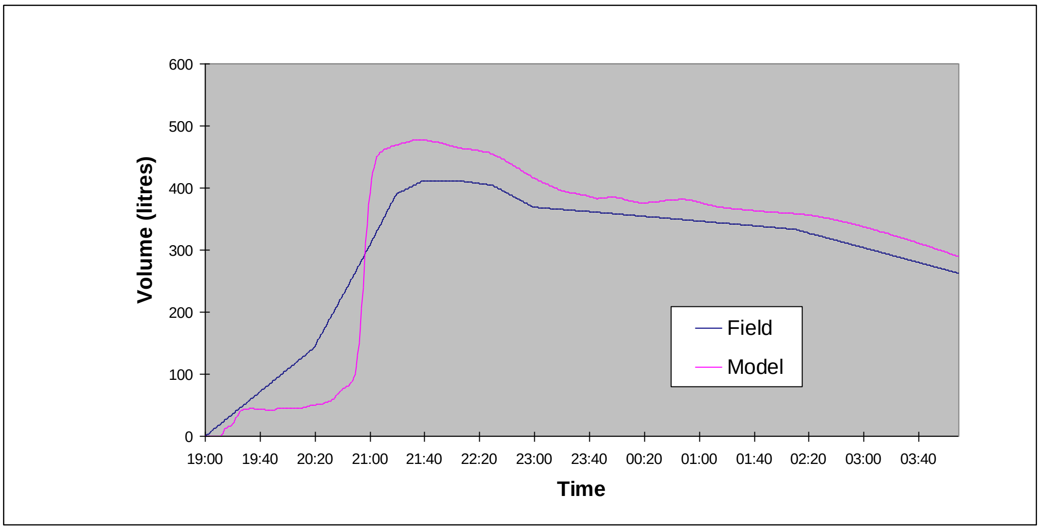


Figure A2.1e July17 Terrace HB5 Water Volume

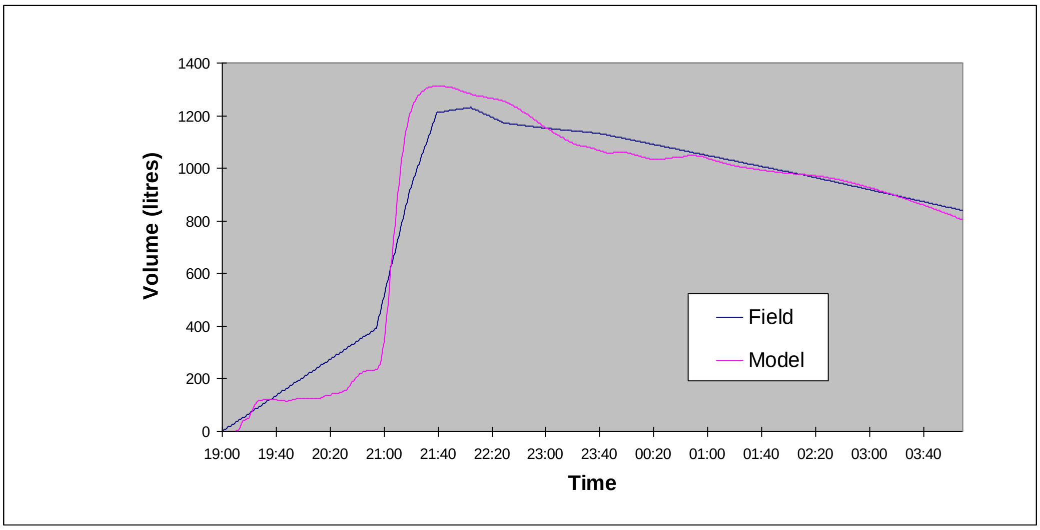


Figure A2.1f July17 Terrace HB6 Water Volume

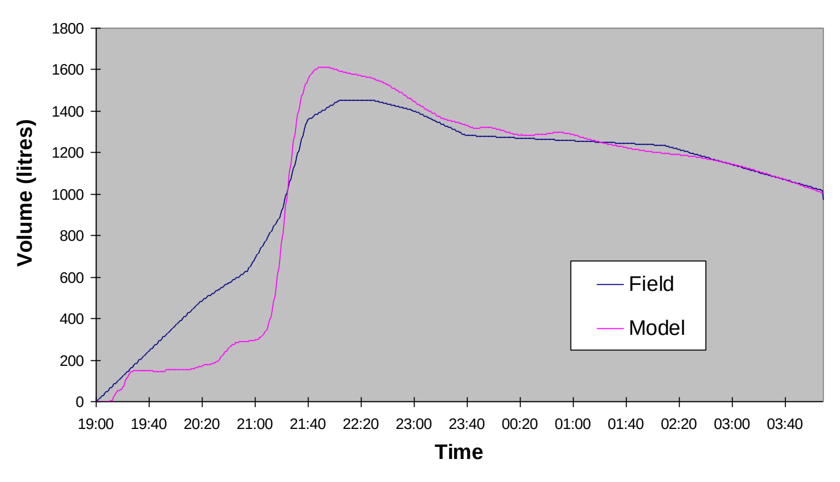


Figure A2.1g July17 Terrace HB7 Water Volume

A2.2 July 19th Event – Khet HB

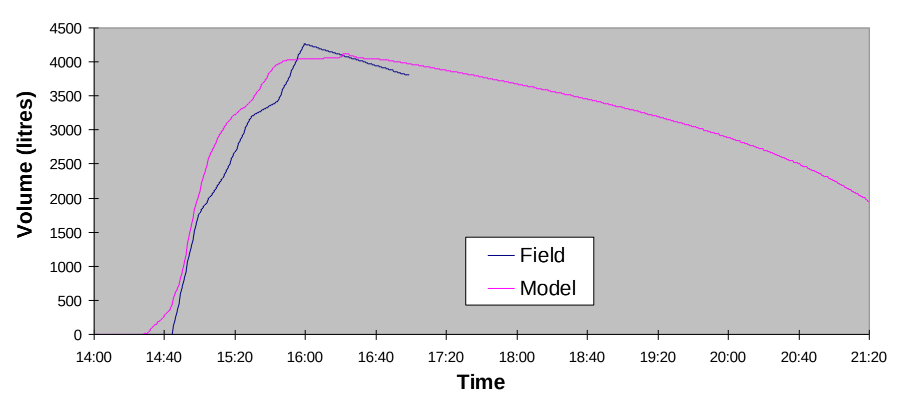
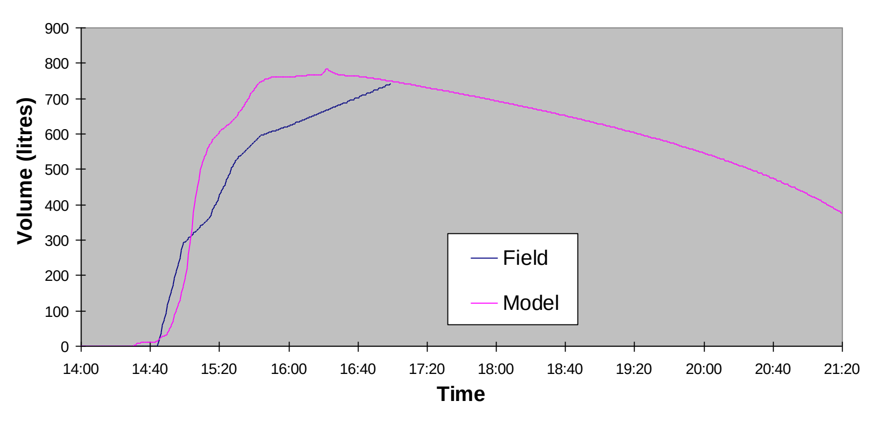


Figure A2.2a July19 Terrace HB1 Water Volume



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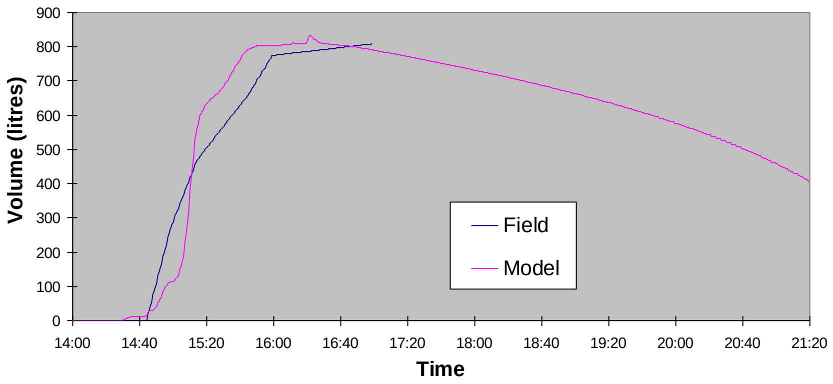
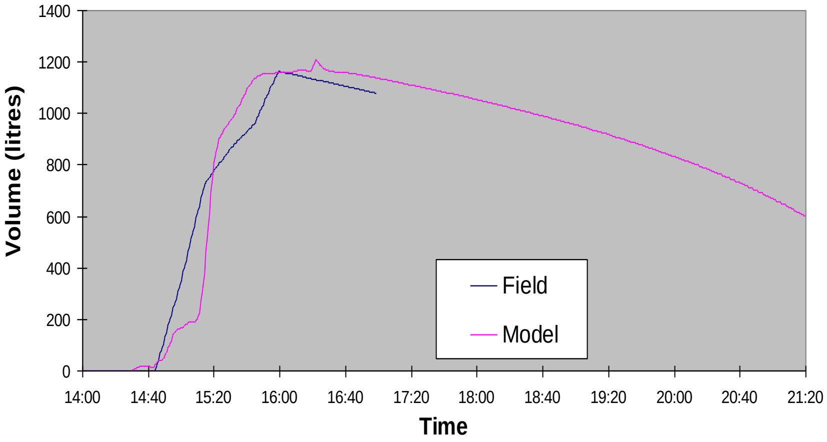


Figure A2.2c July19 Terrace HB3 Water Volume



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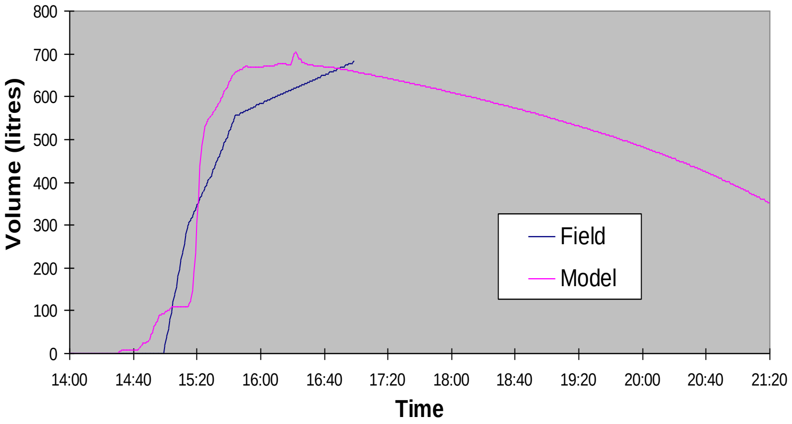


Figure A2.2e July19 Terrace HB5 Water Volume

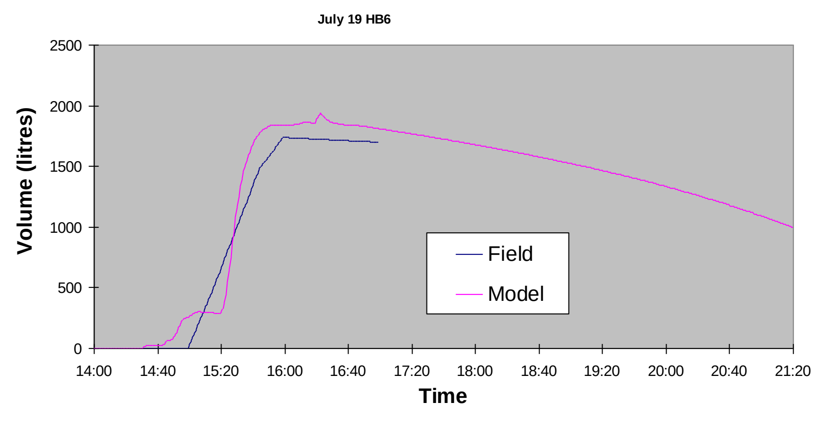


Figure A2.2f July19 Terrace HB6 Water Volume

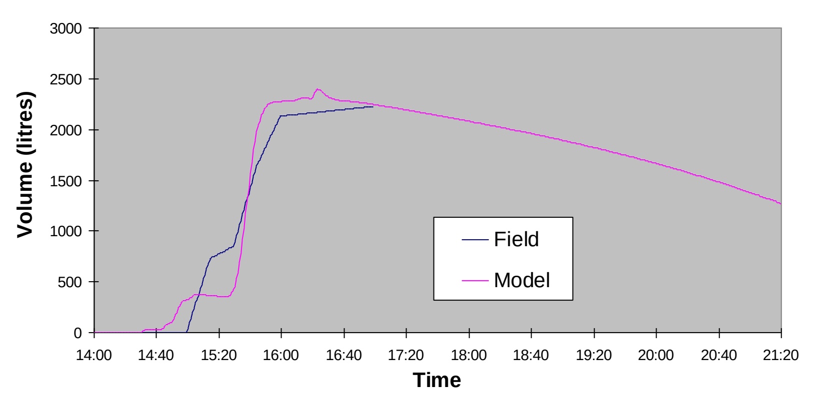


Figure A2.2g July19 Terrace HB7 Water Volume

A2.3 Aug 3rd Event – Khet HB

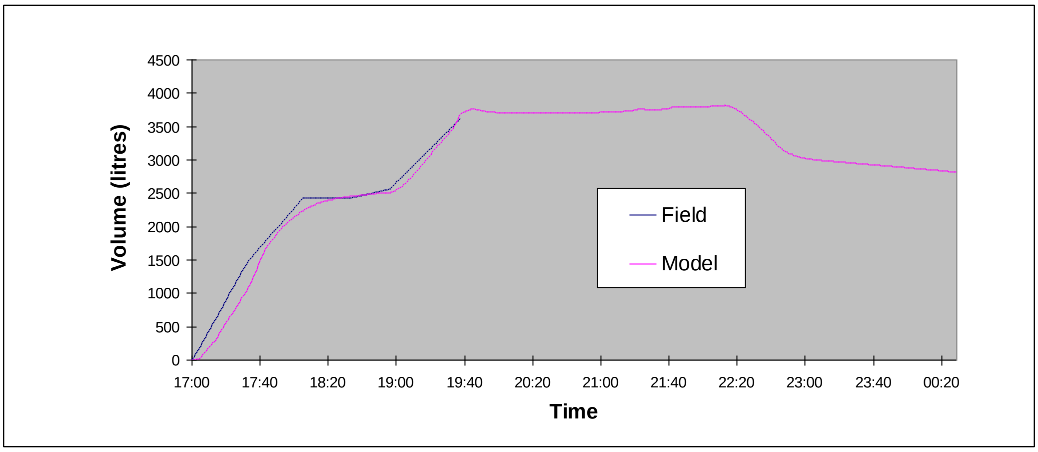


Figure A2.3a Aug3 Terrace HB1 Water Volume

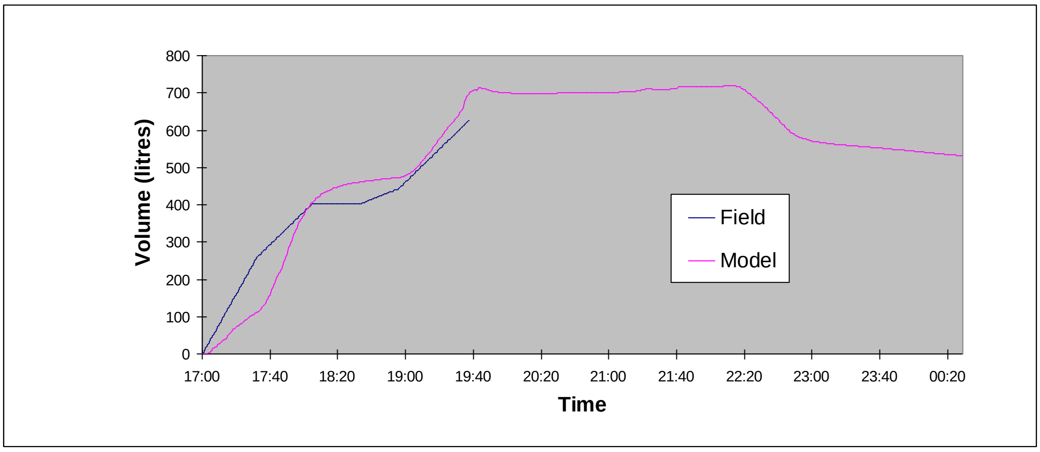


Figure A2.3b Aug3 Terrace HB2 Water Volume

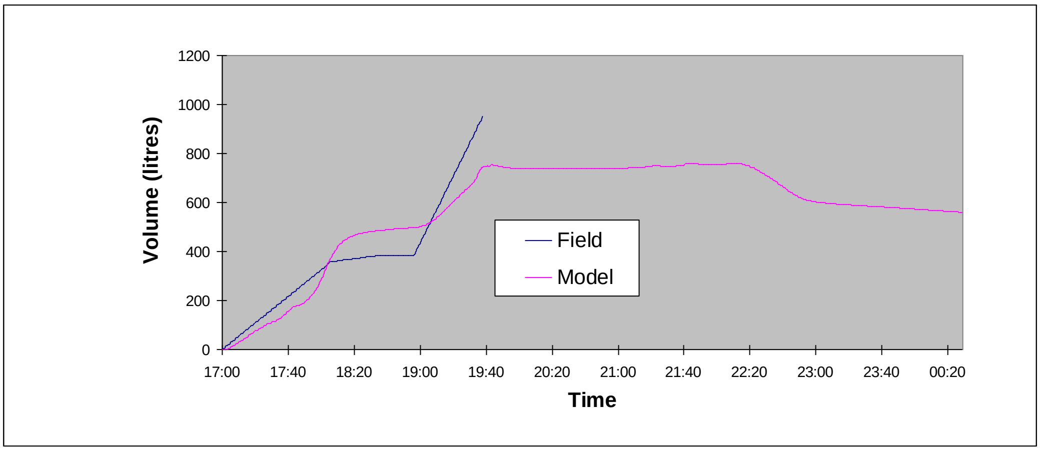


Figure A2.3c Aug3 Terrace HB3 Water Volume

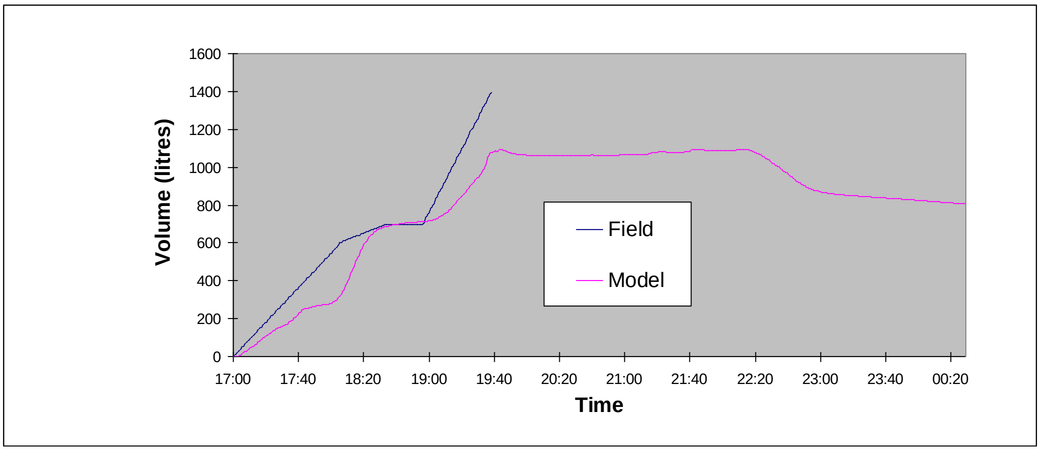


Figure A2.3d Aug3 Terrace HB4 Water Volume

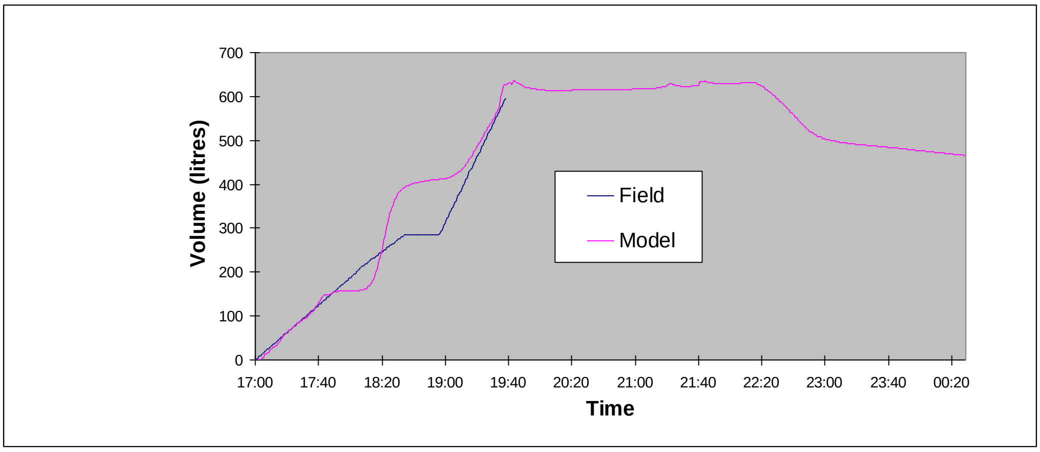


Figure A2.3e Aug3 Terrace HB5 Water Volume

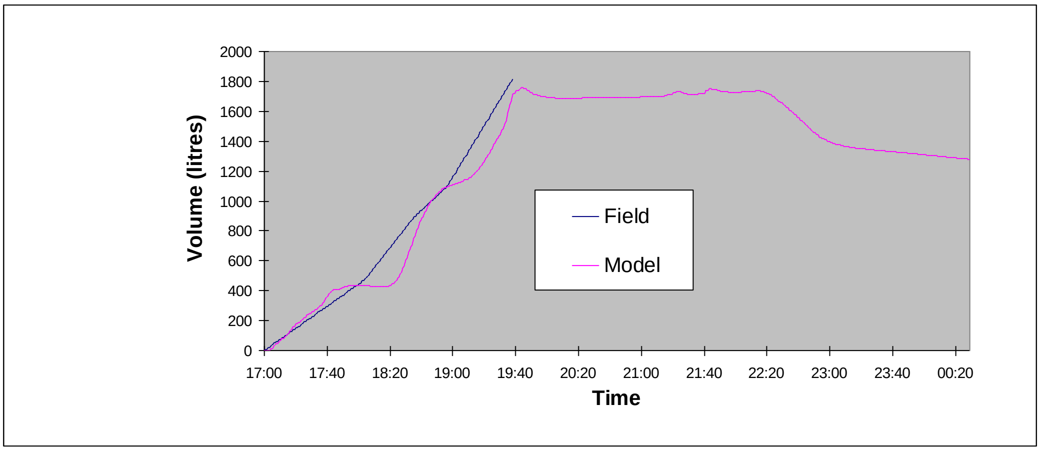


Figure A2.3f Aug3 Terrace HB6 Water Volume

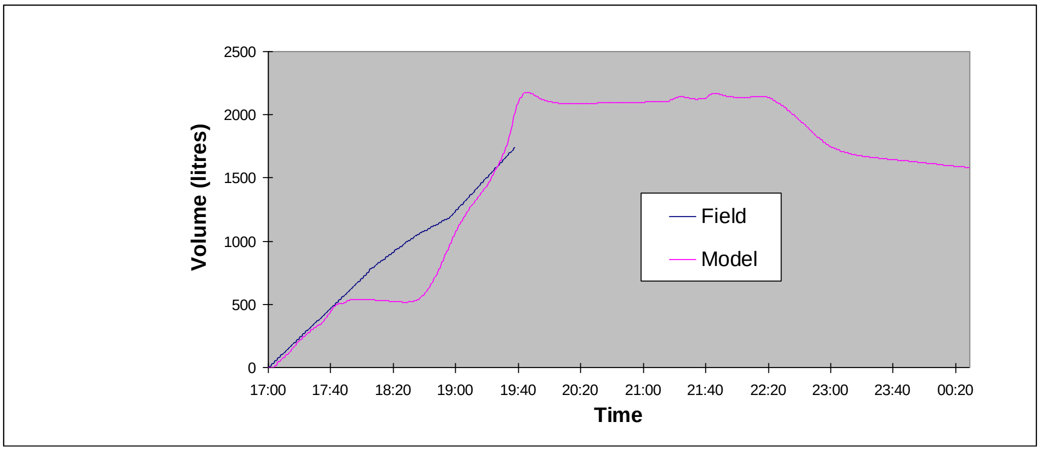


Figure A2.3g Aug3 Terrace HB7 Water Volume

A2.4 Aug 3rd Event – Khet PA

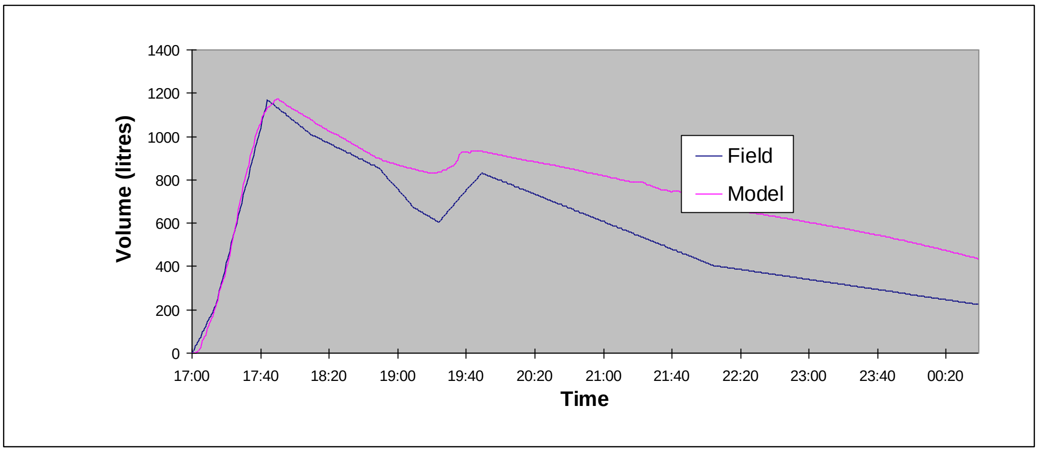


Figure A2.4a Aug3 Terrace PA1 Water Volume

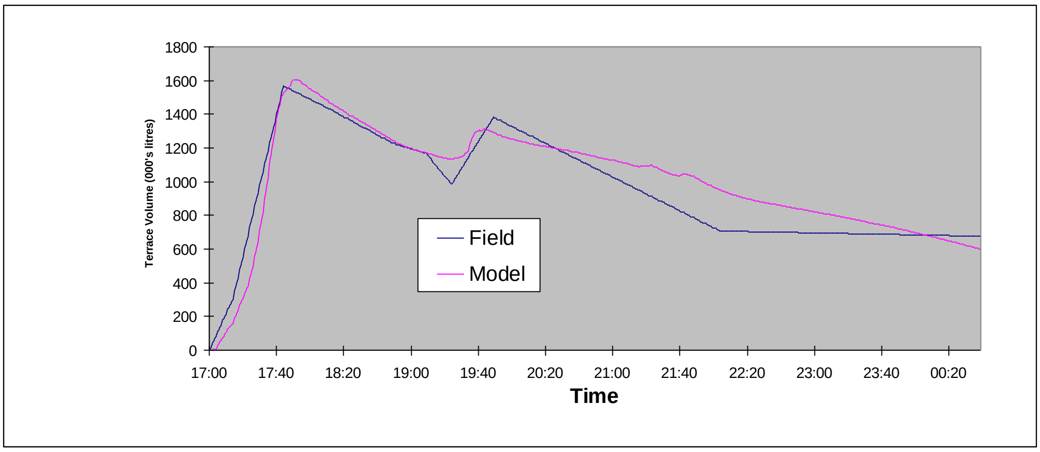


Figure A2.4b Aug3 Terrace PA2 Water Volume

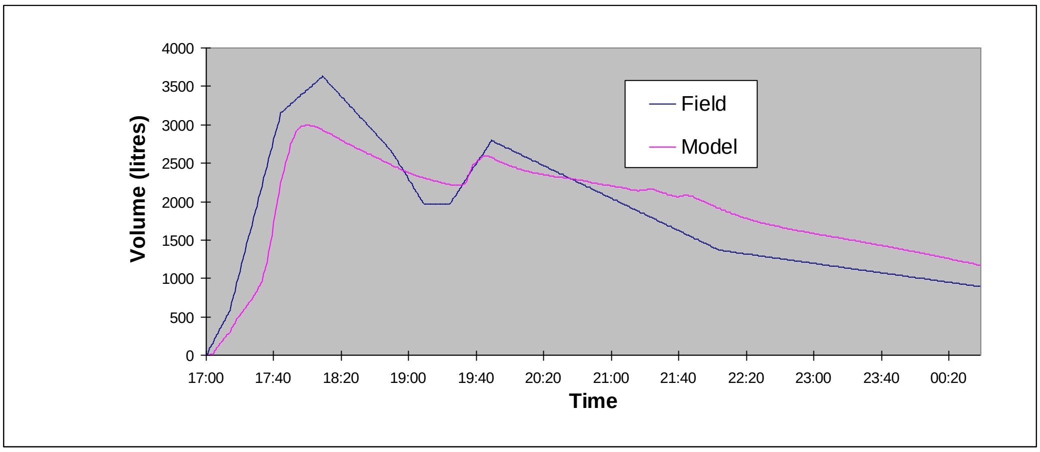


Figure A2.4c Aug3 Terrace PA3 Water Volume

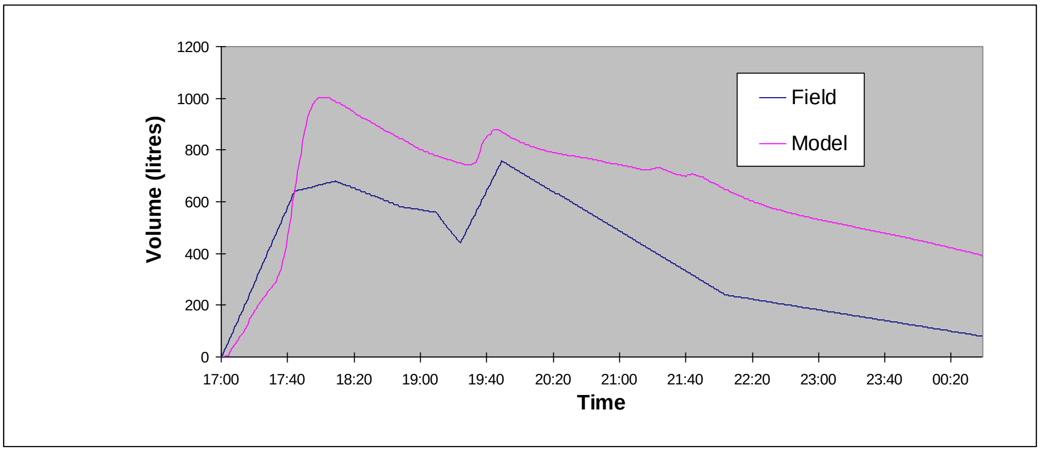
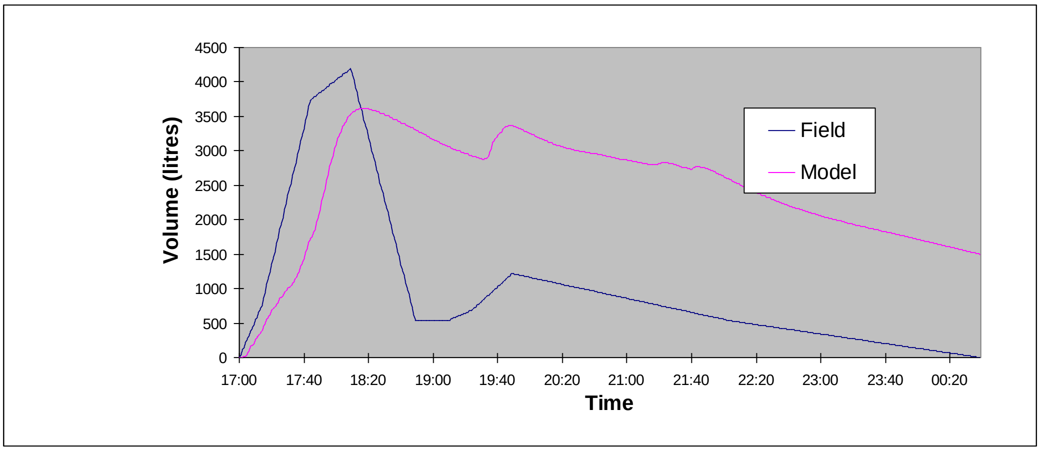


Figure A2.4d Aug3 Terrace PA4 Water Volume



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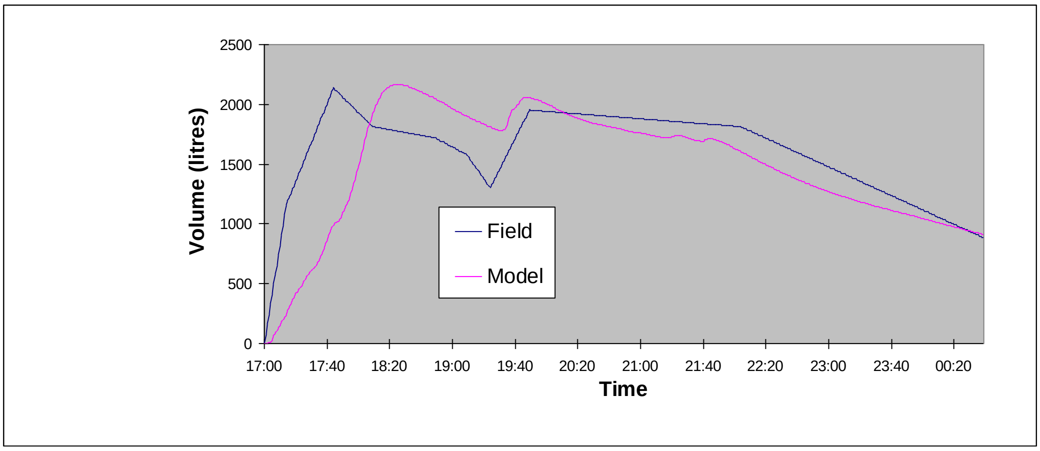


Figure A2.4f Aug3 Terrace PA6 Water Volume

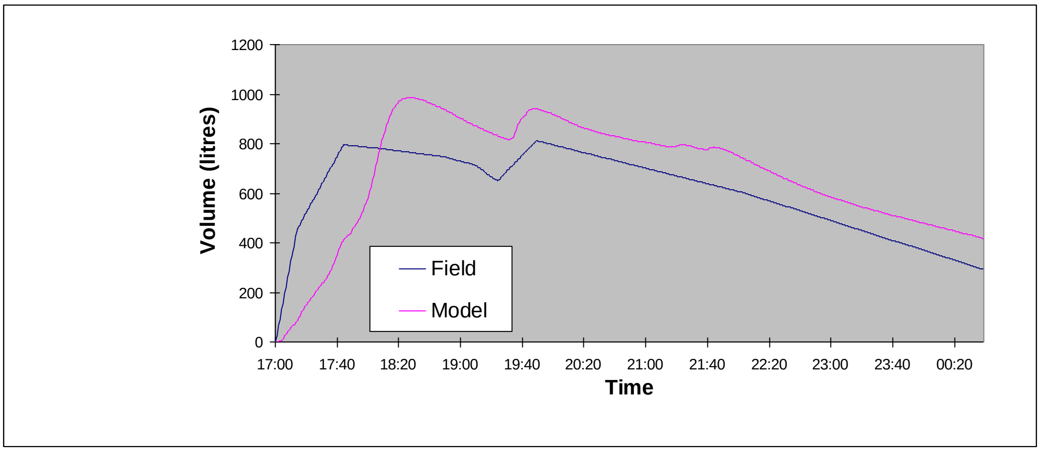
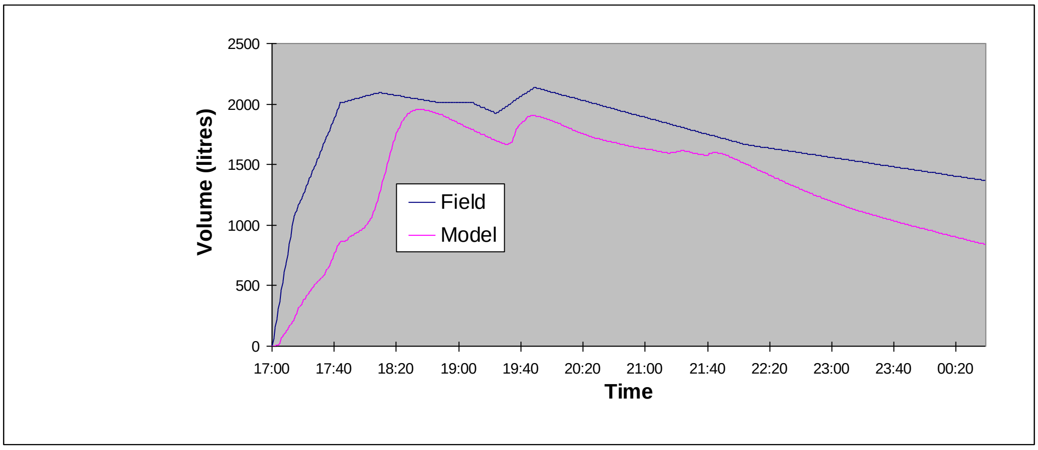


Figure A2.4g Aug3 Terrace PA7 Water Volume



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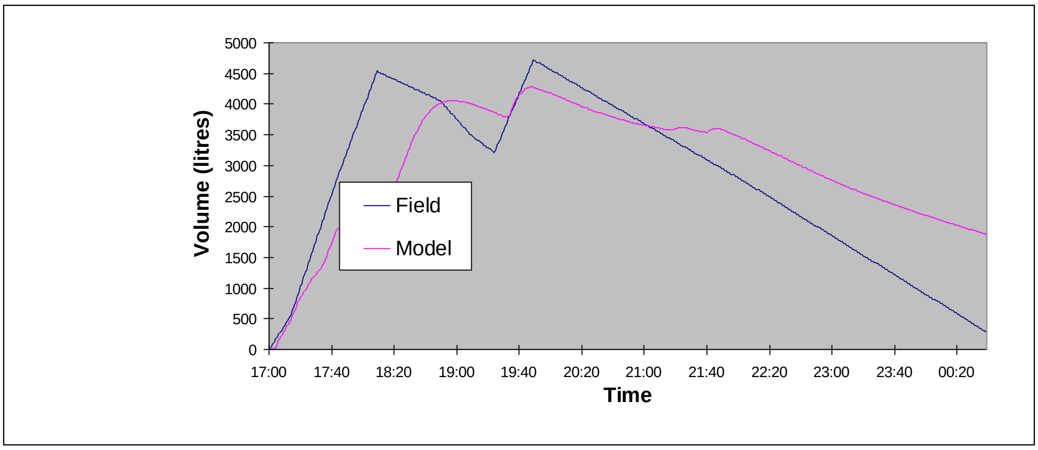

Figure A2.4i Aug3 Terrace PA9 Water Volume

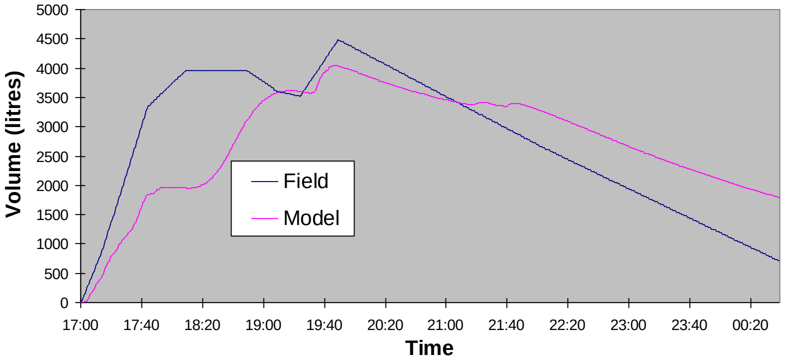

Figure A2.4j Aug3 Terrace PA10 Water Volume

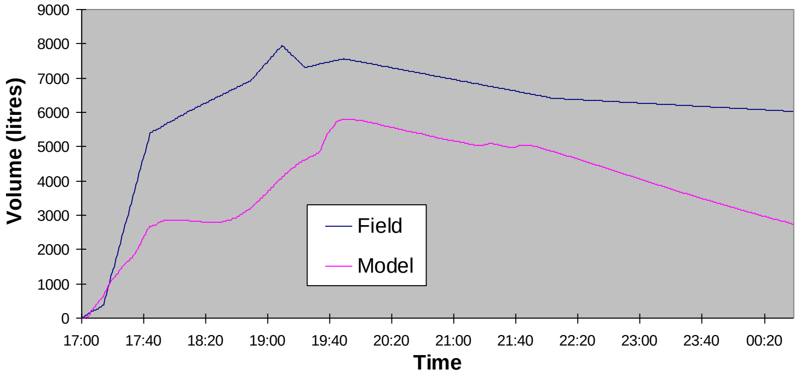

Figure A2.4k Aug3 Terrace PA11 Water Volume

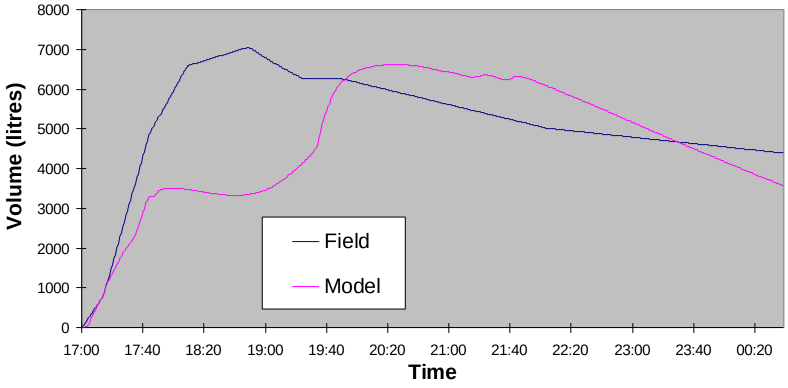

Figure A2.4l Aug3 Terrace PA12 Water Volume

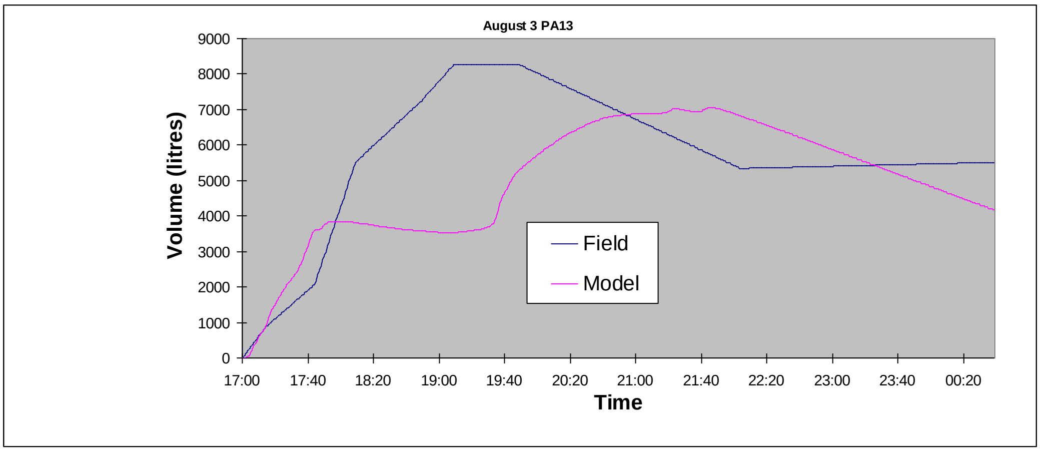

Figure A2.4m Aug3 Terrace PA13 Water Volume

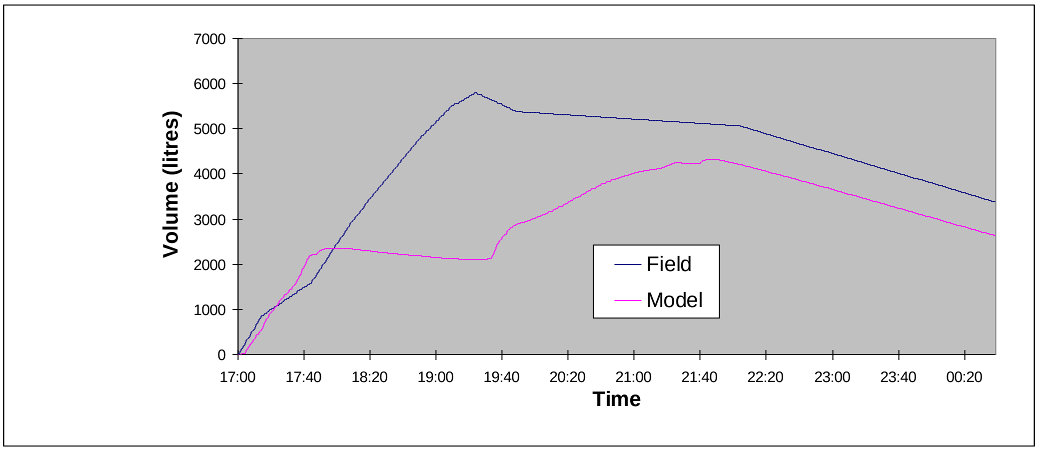

Figure A2.4n Aug3 Terrace PA14 Water Volume

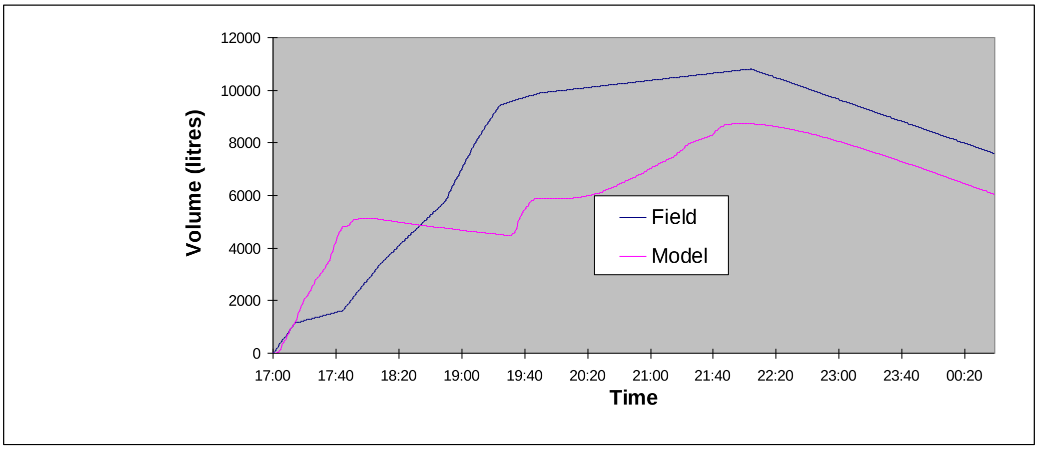

Figure A2.4o Aug3 Terrace PA15 Water Volume

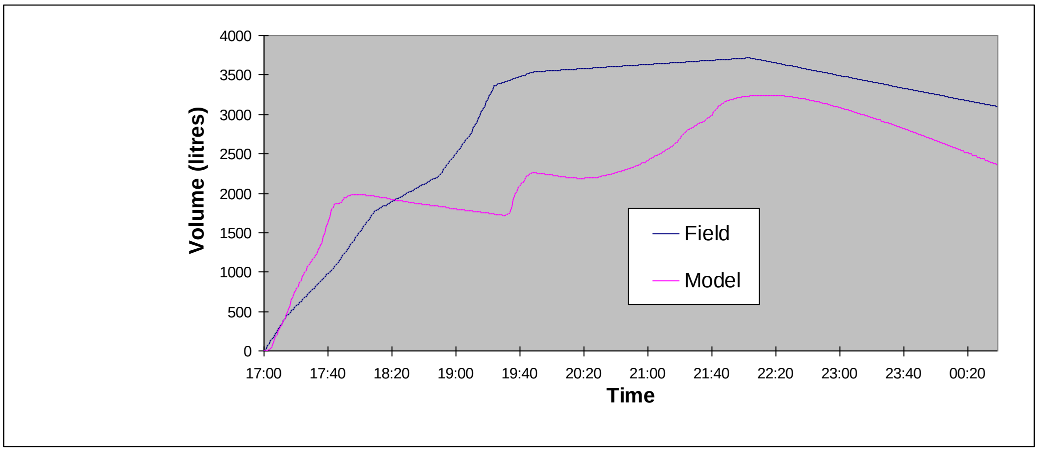

Figure A2.4p Aug3 Terrace PA16 Water Volume

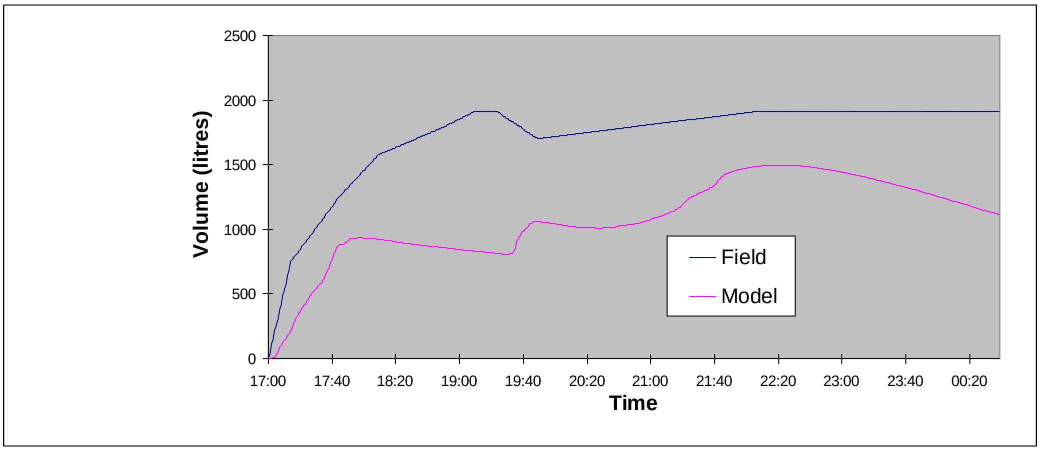

Figure A2.4q Aug3 Terrace PA17 Water Volume

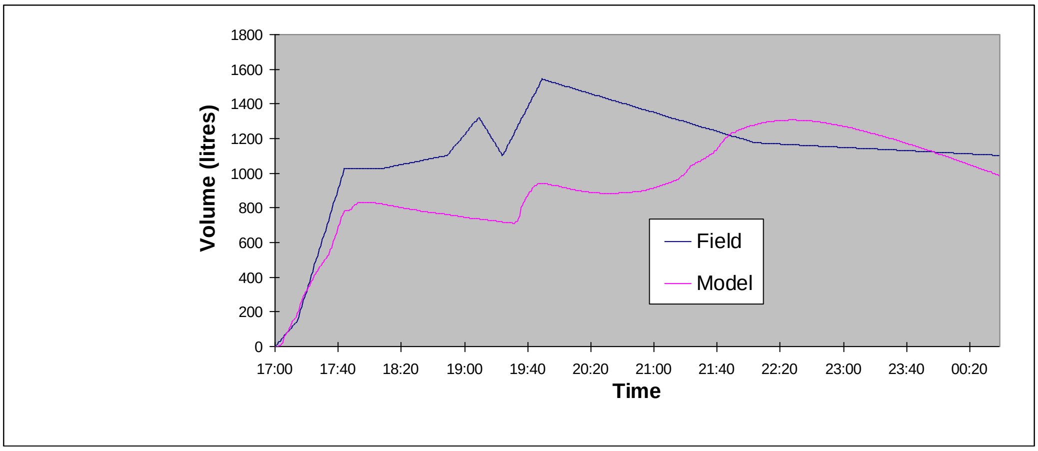

Figure A2.4r Aug3 Terrace PA18 Water Volume

Appendix 3: Model Tables and Operation

A3.1 Introduction

This appendix contains details about the model that should be included in the thesis for reference but are thought too mundane for inclusion in the main text. Sections A3.2 to A3.7 describe in detail the tables of the model, the fields therein and their purpose. Sections A3.8 to A3.x describe in detail the operation of the model.

A3.2 Tables Overview

Two tables to describe the physical characteristics of the terrace/hillslope system:

KhetFlow Terrace Data
KhetFlow Outflow Data

Five tables contain data representing process rates:

KhetFlow Rainfall Data
KhetFlow Irrigation Data
KhetFlow Evapotranspiration Data
KhetFlow Seepage Data
KhetFlow Return Flow Data

The model operation is controlled by:

KhetFlow Control Data

The model also requires that a skeleton table (a table with fields defined but containing no records) be present to receive the results reported by the model:

KhetFlow Results

A3.3 Table: KhetFlow Terrace Data

This table describes the physical characteristics of the khet system currently being processed by the model. It contains one record for each terrace, including data which identify the terrace and its position on the hillslope, data that keep track of the current situation in the terrace during a model application and information as to how the model processes the information held for the terrace.

Terrace Number and Rank - The Terrace Number is a unique identifier for the terrace, usually but not necessarily a sequential number. Terrace Rank is also a unique number applied to the terrace and required by the model to ensure orderly processing. In a series of linear terraces the terraces are ranked sequentially from number 1 at the top of the system to n at the bottom, where n is the number of terraces. In a complex ‘branching’ terrace system the top terrace is number 1 and the terraces are numbered so that a terrace with a lower number always discharges into a terrace with a higher number. In most cases the terrace number and terrace rank will be the same. It was envisaged that when collecting field data in complex terrace systems terrace numbers could inadvertently get out of line so the ranking system was introduced to ensure that this could be corrected at the modelling stage and processing would occur in the correct order.

Terrace Description:

Area	m^2	
Capacity	litres	
Bund Height	mm -	effectively maximum water depth

Current Terrace Position:

Volume	litres	
Water Depth	mm	
Change in Storage	litres -	during the previous iteration

These fields contain the data calculated for this terrace by equation 2.1 and are updated after every model iteration as the terrace is processed by the model.

Terrace Inflows and Outflows:
Each terrace can have up to 5 inflow points and 5 outflow points. These have to be determined before the model processing starts and are allocated as follows:

Number of Inflows – Number of inflows allocated
Inflow 1 – identifier of inflow on Outflows Table, if allocated
Inflow 2 – identifier of inflow on Outflows Table, if allocated
Inflow 3 – identifier of inflow on Outflows Table, if allocated
Inflow 4 – identifier of inflow on Outflows Table, if allocated
Inflow 5 – identifier of inflow on Outflows Table, if allocated

Number of Outflows - Number of outflows allocated
Outflow 1 – identifier of outflow on Outflows Table, if allocated
Outflow 2 – identifier of outflow on Outflows Table, if allocated
Outflow 3 – identifier of outflow on Outflows Table, if allocated
Outflow 4 – identifier of outflow on Outflows Table, if allocated
Outflow 5 – identifier of outflow on Outflows Table, if allocated

Each Inflow and Outflow field contains a reference to a record on the Khetflow Outflow Data table, which contains the information about the outlet required by the model. The convention used is that outflows from a particular terrace are labelled by consecutive letters; for example, 3 outflows from terrace 6 would be labelled 6A, 6B and 6C. The outflow from one terrace is the inflow to a terrace below it in the system and it is essential to the integrity of the system that the same label is used to indicate inflow to the terrace below, for example, terrace 6 might receive inflow from terraces 3 and 5 which might be labelled 3C and 5A.

The Number of Inflows and Number of Outflows fields control how many inflows/outflows are present and thus processed for each particular terrace. It is the model convention to set the Inflow/Outflow label field to '-1' for Inflows and Outflows fields not needed for a particular terrace. Even if a terrace label contains a valid reference, it will be ignored if it is higher than the number of Inflows/Outflows set for this terrace.

Default Values:
Default Evapotranspiration - ml per minute per m^2
Default Seepage - ml per minute per m^2
Default Return Flow - ml per minute per m^2

These are default values for these processes on this terrace that can be used instead of data held on the data tables. If set, these rates override those held in the process data tables and the processes described are determined to have a constant rate for the duration of the model. This is useful when testing the sensitivity of the model and when there is a requirement to estimate process rates. These fields are turned off by setting their value to -1.

Discharge Values:

Weir inflow	ml/min
Oflow in	ml/min
Weir Outflow	ml/min
Oflow out	ml/min

These are memo fields updated for every iteration as the model runs, holding the total of the discharge rate of all the inflows or outflows of the terrace and the total discharge rate of any overflow.

A3.4 Table: KhetFlow Outflow Data

This table contains data to control the routing of water between terraces and holds values for the current rate of discharge across the outflows. The records in this table can be thought of as ‘sub-records’ of each terrace record on the Khetflow Terrace Data table as there is a record in this table for each of the inflow/outflow weirs referred to on the terrace records. In this way each of the inflow/outflow records on this table is ‘owned’ by a terrace record and as the model is processing data for a terrace it will reference the ‘sub-records’ on this file as required. As the outflow from one terrace is the inflow to another, each inflow/outflow record on this table needs to be referenced twice; once when the model is processing the outflow from a terrace on the Terrace Table and once when the model is processing the inflow to a different terrace. The ‘ownership’ of each of the inflows/outflows on this table is thus shared between two terraces on the Terrace Table.

A maximum of five records on this table can be ‘owned’ by a terrace record as inflows, matching the maximum number of inflows allowed to each terrace, and a maximum of five records on this table can be ‘owned’ by a terrace record as outflows, matching the maximum number of outflows allowed from each terrace.

The data held for each outflow is as follows:

Terrace Data:

Terrace Number:	This is the number of the terrace from which this outflow discharges.
Outflow Identifier:	The unique identifier of the outflow weir, for example 2A 8C, where the number is the terrace number and the letter identifies the outflow within the terrace.
Terrace to:	The terrace into which this outflow discharges.

Outflow Dimensions:

Height	mm
Width	mm
Clearance	mm - height of the base of the outflow above the terrace floor.

Discharge:

Current Flow	ml/min
Flow Height	mm - height of water flowing through the outflow.
Overflow	ml/min - overflow from the terrace, if occurring.
New Flow	These three fields are memo fields updated for every iteration as the model runs, holding values calculated for the next iteration of the model.
New Height	
New Oflow	

A3.5 Tables Containing Data Representing Processes

There are five tables containing data representing processes:

KhetFlow Rainfall Data
KhetFlow Evapotranspiration Data
KhetFlow Seepage Data
KhetFlow Return Flow Data
KhetFlow Irrigation Data

Each of these tables contains data representing the rate at which each operates during the application. As far as the operation of the model is concerned, the function of these tables is very simple. Each record on the tables contains two important fields:

- **Minute:** The number of (model) minutes or iterations since the model application started.
- **Rate**: in ml/min/m^2 - the rate of the process during the current minute/iteration.

Apart from the table for KhetFlow Rainfall Data these are the only two fields in the tables.

The purpose of these tables is to present to the model processing routines data determining the rate at which each of these processes is operating at any particular point in time during the model application. As such, for each minute/iteration of the model operation each table contains the pre-set rate pertaining to the process it represents. The rates are taken from these tables and fed into the continuity equations for the terraces and the net effect of the processes calculated. All rates are held as millilitres per minute per m^2 (ml/min/m^2) as a standard unit and because it is important to allow the model to adjust the rate according to the area of the terrace currently being processed.

KhetFlow Rainfall Data table has additional fields because when the model is being used to replicate field situations (as opposed to hypothetical situations such as the sensitivity analysis described in Chapter 5) prior processing is required for the rainfall data. These data are extracted from automatic tipping bucket raingauges and converted to be used by the model. Automatic tipping bucket raingauges record the number of tips of a bucket of known volume each minute during a storm on a small internal storage device. The data from the storage medium are downloaded to Excel spreadsheets, then transferred to the Access database, where a query is applied to produce the first three columns illustrated in Table A3.1 - ‘Hours’, ‘Minutes’ and ‘Tips’.

Table A3.1 Example of Rainfall Data Converted from Automatic Raingauge

Hour	Min	Tips	Model Run Time	Intensity
17	9	1	1	0.2
17	10	1	2	0.2
17	11	2	3	0.4
17	12	1	4	0.2
17	13	1	5	0.2
17	14	1	6	0.2
17	15	1	7	0.2
17	16	1	8	0.2
17	17	1	9	0.2
17	18	2	10	0.4
17	19	2	11	0.4
17	20	2	12	0.4
17	21	2	13	0.4
17	22	2	14	0.4
17	23	3	15	0.6
17	24	2	16	0.4

The final two columns ‘Model Run Time’ and ‘Intensity’ are calculated by the query to adapt the data for use by the model. ‘Model Run Time’ is the conversion of the actual time of the storm to the Model time - the time during the model run at which the storm will be applied; ‘Intensity’ is the number of tips in that minute multiplied by the calibrated bucket size, giving the rainfall intensity during that minute. If there were no tips for one or several minutes the eventual tip volume was divided between the previous minutes by straight line averaging.

A3.6 Table: KhetFlow Results

The results of each application are written to an Access table ‘Khetflow Results’, which is then stored by renaming it as appropriate to the application. These can be seen in the Access databases “KhetFlowDatabase1” and “KhetFlowDatabase2” on the accompanying DVD. For example, ‘Results HB Aug3-216’ would be the results from Khet HB for the storm of August 3rd, model application number 216. The results table captures the value of each process and terrace variable for every terrace for every minute/iteration of a particular model run. The model thus generates large volumes of data; an application of the model simulating a 24 hour period on a 25 terrace system would generate 1440 minutes x 25 terraces = 36,000 records, each containing up to 17 variables. Such a dataset is clearly unmanageable in its raw form and is interpreted by a series of Access queries and Excel spreadsheets to allow presentation in a meaningful manner. This process is described in Section 4.3 below.

A3.7 Table: KhetFlow Control Data

This table contains variables that control the operation of the model; for instance, the number of minutes for which the model runs, how often the results are printed to file and many of the default values for the variables. This table captures the values set by the Visual Basic Screen (Figure 4.5) that controls the model.

A3.8 Operating the KhetFlow Model: Overview

There are four stages in the operation of the model:

1. Set-up data in the Access database.
2. Input variables that control the model application.
3. Run the main processing routines.
4. View and analyse the model results.

Stage 1, setting up data in the Access database, has been described in the main text, as has viewing the results (Stage 4). Analysis of the results of individual applications is described in later chapters as particular applications are processed. This section details Stages 2 and 3, explaining how and why control variables are set up to process various simulations and how the main processing routines are operated.

A3.9 Stage 2: Input Variables that Control the Model Operation

Figure 4.5 is a replication of the Model run screen, repeated here for convenience. The screen is presented to the user at the start of each application and the variables set as required. Yellow boxes are general headings, red boxes are headings related to individual control variables, which are input by typing into the respective white boxes. The largest white box is the run clock, which is for display only. The operation of the model is controlled via the grey command bars which are ‘clicked’ to perform various actions. The large grey display box allows the Khetflow Terrace Data table to be viewed continuously.

Control variables are input by clicking on the appropriate white box and typing the input fields as described. The input is stored in the table referred to in Section 4.3.6, Khetflow Control Data Table. Control variables are used as follows:

Setting Terrace Variables:

Reset Terrace Areas: In the field very few terraces are exactly the same shape or area. However, the model is first applied to idealised sets of identical linear terraces to test the sensitivity of the system to the change of individual variables (see Chapter 5). Setting the ‘Reset Terrace Areas’ field resets the area of all terraces in the system to the value supplied so that the sensitivity of the system to variation in terrace area can be tested. If the field is set the capacity of the terraces is automatically recalculated and amended to reflect the new area. This field is set to -1 if it is not to be used.

Reset Bund Height: The bund is the lip of earth round the front and sides of the terrace that keeps the water in, the bund height is effectively the maximum depth of the terrace. In practice this varies little from terrace to terrace. The height can be set at different levels for individual terraces but when the model is first applied to identical terraces setting this field resets the bund height and therefore the maximum depth of all terraces in the system to the value supplied to allow sensitivity analysis. If this field is set the capacity of the terrace is automatically recalculated to reflect the new depth. This field is set to -1 if it is not to be used.

Reset Start Volume: Setting this variable fixes the start volume of water in all the terraces in the system. The volume is set irrespective of the area of the terrace and the depth of water is automatically recalculated. Setting this variable is again useful when undertaking sensitivity analysis. This field is set to -1 if it is not to be used.

Reset Outflow Height:

Reset Outflow Width:

Reset Clearance: Setting these values sets the dimensions of all of the outflows in the system, effectively setting the dimensions of the outflow 'weir' used to calculate discharge rates. Clearance is the height of the base of the outflow above the soil surface of the terrace; height is the distance from the base of the outflow to the lip of the bund; width is only relevant if the weir is U-shaped - see 'Weirs' below. These fields are set to -1 if they are not to be used.

Inconsistencies in the above settings: If any of the above are set in an inconsistent manner eg. volume greater than capacity, weir height greater than bund height; the model will warn the user and set the variables in a logical way.

Setting Process Variables:

Default Rainfall

Default Irrigation: These are default system values for these processes that can be used instead of data held on the data tables. If set, these rates override those held in the process data tables and the processes described are determined to have a constant rate for the duration of the model. This is useful when testing the sensitivity of the model and when there is a requirement to estimate process rates. If 'Default Rainfall' is set rainfall is applied to all terraces in the system at this rate; If 'Default Irrigation' is set it is only applied to those terraces taking water directly from the irrigation canal. These fields are set to -1 if it is not to be used.

Flow Coefficient

Clod Height

Minimum Flow Depth

Crop Stage

Crop Parameter

Size Parameter

Flowline Parameter: These fields have been explained in description of the model given in section 3.2. They are set as appropriate or set to -1 if not to be used.

Diversion Threshold:

Divert if full?

Halt to Adjust?: Farmers design terrace systems so that in normal conditions outflow is restricted and water is ponded in the terrace at reasonable levels and it is normal farmer practice to build terrace systems with only 10 to 30 ‘drops’ between irrigation canals or natural boundaries to avoid a build up of water in the system during heavy rain. However, during very intense rainfall there is a danger that the system cannot cope with the amount of water input and that water will overtop the bund of some or all of the terraces and start to cascade down the hillside in an uncontrolled manner. This causes severe erosion of the terrace bunds and results in considerable damage to the terrace system. As most farmers live near to the their terraces it is quite normal for them to open additional outlets to adjacent gullies, stream or canals during heavy storms, if possible, to relieve the pressure on the system. One series of applications of the model (see Section X) is to investigate the conditions under which this becomes critical and to quantify the effectiveness of the farmer actions. These variables are set as part of that exercise. If the ‘Divert if full?’ flag is set, when the volume of water in any terrace reaches the threshold set (% of capacity) the model will open an additional outflow taking water away from the system, simulating the opening of a new outflow to an adjacent stream. Similarly, the ‘Halt to Adjust’ flag stops the model application if overflow occurs and allows the user to adjust outflows. However, additional outflows can only be utilised if terraces are on the boundary of the system. This is controlled in the model be only allowing extra outflows from individual terraces that have the ‘Divert’ flag set on the record in the Khetflow Terrace Data table. The two flags are set by ‘clicking’ on the appropriate white box, which will then display a tick. (Note: This function operates by adding 1 to the number of outflows set for the terrace on the Khetflow Terrace Data table. The information regarding the outflow must exist on the Khetflow Terrace Data record and there must be a record for the additional outflow on the Khetflow Outflow Data table).

Setting Other Control Variables:

Weirs: The user can decided if a particular model application will utilise U-shaped or V-shaped weirs. It this study all but one of the field applications modelled used V-shaped weirs.

Data source is file (tick) or default: Setting the data required for the model on the appropriate Access tables has been described above. However, when the rate of a process is constant for the duration of the model it is simpler and more convenient to set a default value for the process. This is also very useful during sensitivity analysis. If a tick (click mouse on the appropriate box) is inserted in any of the boxes for the 5 processes the default value is used. The default for rainfall and evapotranspiration is held for the whole system on the Khetflow Control Data table; the default for canal inflow is also held on the Khetflow Control Data table and applied to every inflow from an irrigation canal; the default for seepage and return flow is held for each individual terrace on the Khetflow Terrace Data table (but see 'Hillslope Shape' below). If the default is not selected but the any of the data tables are empty the model will warn the user and also use the default value set on the table.

Run Clock: is the model minute/iteration currently being processed. This field is for information only and cannot be set by the user.

Run Minutes: The model will operate for the number model minutes set, ending when the model run clock reaches this minute. Each model minute will trigger one iteration of the model.

Reporting Period: During normal operation the model writes a record containing 47 fields detailing the state of the model variables to the results file for every terrace for every minute/iteration of the model application. A 24 hour application of the model to a system of 25 terraces would generate 36,000 records and 1,692,000 fields of data. These can be viewed more coherently by using the query tools described above and in the relevant sections, but it is sometimes more convenient to limit the number of records produced. If the reporting period is set the model will only write results to the file for each terrace if the model minute/iteration is exactly divisible by the period set. Note that the records then recorded are 'snapshots' of the system at the time of the minute being processed, not cumulative values since the previous record was written.

Irrigation Inflows Closed: If this is set and the default value for Irrigation has been selected (but not if the data is being taken from the Khetflow Canal Inflow table) irrigation will cease when the model run clock reaches the minute indicated by this field. This field is set to -1 if it is not to be used.

Storm Start

Storm End: If these fields are set the and the default value for rainfall has been selected (but not if data is being taken from the Khetflow Raindata table) rainfall will start when the model run clock reaches the minute indicated in the 'Storm Start' field, and cease when the model run clock reaches the minute indicated by the 'Storm End' field. These fields are set to -1 if they are not to be used.

A3.10 Stage 3: Running the Main Processing Routines

Once all control variables have been input the user clicks on the command bar 'Click Here to Set-up Model'. This performs various set-up routines, including examining the data for inconsistencies, and presents the command bar 'Set-up Completed - Click Here to Run Model'. The user can then either click this bar to run the application or click the 'Click Here to Run Set-up Again' command bar to change the set-up. The command bar 'Click Here to Examine Data' presents a different screen which allows the user to view and amend any of the tables. In this supplementary screen each of the nine tables is presented as a 'Data bar'. Clicking on any of these bars opens the appropriate table and data therein can be changed by simple overtyping, the data is saved directly to the appropriate table in the Access database. The main screen is recalled by clicking the command bar 'Click Here to Return to Main Screen'. On doing so the user is forced to run Set-up again so that the model can check that the data retains consistency. It is recommended that only minimal data changes are made in this manner, perhaps to fine tune a particular application. Data should normally be set up by direct input to the tables. The Terrace Data Table is permanently displayed on the main screen in the Datagrid

‘Khetflow Terrace System’ so that the position of the terraces can be viewed at any time during the application. Terrace variables can be amended by directly typing into this grid but if so the user should ensure that Set-up is re-run before the application is performed.