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Evaluation of the hydrological environment of peatland by using Peatland Tank Model

(泥炭地タンクモデルを用いた泥炭地水文環境の評価に関する研究)

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SUMMARY

Peatland is an important ecosystem due to its organic peat soil and unique hydrological environment. The peat soil is characterized by high carbon content, complex structure, and high water-holding capability. In peatland, the groundwater table (GWT) is usually maintained at high level and the hydrological behavior is specific. Consequently, monitoring of GWT fluctuation is indispensable for the investigation of peatland hydrology, and quantitatively and exactly evaluating the peatland hydrological conditions are necessary for the reservation and proper usage of peatland. In this study, we proposed a new method based on Peatland Tank Model (PTM) for evaluating peatland hydrological environment.

The objective of this study is to quantitatively express the shallow GWT fluctuation patterns and to evaluate the changes of hydrological environment. PTM is a simple one dimensional water balance model and its prototype has seven parameters (C , $A1$, $A2$, $A3$, $HA1$, $HA2$ and $HA3$). To be specific, coefficient C represents the GWT increase owing to rainfall. Coefficients Ai (i : number of plugholes, $i = 1, 2, 3$) ($0 \leq Ai \leq 1$) and HAi are the size and height of the i^{th} plughole, respectively. C and Ai are unit less. As indicated by the name, PTM models the peatland hydrological as a water storage tank. In this way, the GWT fluctuations of a peatland can be represented by the variations in water levels of a tank.

In this study, the operational platform of PTM is a program using Microsoft Excel's macro function. The operation of PTM only requires time-series data of GWT and rainfall. It does not need a series of parameters representing peat properties and hydraulic characteristics such as bulk density, hydraulic conductivity, specific storage

and specific yield. In addition, this model does not need to deal with geographical information such as topographic information, soil type and land use. So, the evaluation method using PTM requires less measurement and the operation can be implemented with very low computational complexity. In the computer simulations based on PTM, GWT fluctuations can be reproduced with a good accuracy of a few centimetres and the subtle variations in GWT fluctuation patterns can be distinguished by configuring the parameters of this model.

The effectiveness and the flexibility of PTM were validated by simulations using the 29-year groundwater data which were collected from Gensekaen of Sarobetsu Mire and Ochiai of Sarobetsu Mire, northern Hokkaido, Japan.

Firstly, in Gensekaen of Sarobetsu Mire, GWT data and rainfall data have been continuously monitored at three sites (E, W and WB) covered by different vegetation communities. The 29-year GWT data were absolute height above sea level because the level survey had been performed here annually from 1983 to 2013. On the basis of the actual computation experience of PTM, four rules and two simulation cases were established and the number of parameters was reduced from original seven to three or two. The fluctuation patterns of GWT can be numerically expressed by the parameters of PTM. The various characteristics of GWT increase could be represented by parameter C (a large C value indicates a large ratio of GWT increase). The difference in GWT decrease could be described by parameter Ai and HAI (a large AI value or deeper HAI indicates greater basic and constant water loss from the peat layer, and a large $A2$ value indicates rapid water loss in the upper peat layer). Thus, large values of parameters C and Ai indicate that the GWT response to rain and dry events had wide variation and large ratios of water table increase and decrease. Moreover, these

parameters could also represent properties of peat soil. A larger C value indicates smaller effective porosity and water storage of peat. A larger A_i and deeper $HA1$ values means that the GWT decreases rapidly so the peat becomes drier during rain-free periods. Long-term variations of the parameters reflect peatland stability. There was drastic variation in the parameters at observation site (WB) dominated by a *Sasa* community from 1991 to 2013, whereas long-term parameter changes were slight at the other two sites (E and W) from 1983 to 2013. Site WB had unstable GWT conditions relative to those at E and W, which mean that the latter two sites were tolerant of annual climate conditions, whereas WB was susceptible to those conditions.

Secondly, in Ochiai of Sarobetsu Mire, three sites (D, M and U) near drainage ditch and peat mining location were observed for collecting rainfall and GWT data, which were measured without certain elevation references or benchmarks (i.e., sea level or ground surface). Through establishing two simulation cases and three rules, such type of GWT data were effectively used for evaluating the changes in GWT fluctuation patterns and site differences in hydrological conditions, even if these GWT data have no common meaning or information in relation to the ground surface or elevation above sea level. Meanwhile, the number of parameters was reduced from the seven to three or two. The simulation results reveal that, wide GWT fluctuations were reflected by large parameter values (parameter C , A_i and $HA2-HA1$). The GWT fluctuation at site (D) near a drainage ditch along the peat mining location was the most drastic: the magnitude of GWT increase in response to rain events was maximum (parameter C) and the amount of water loss was greater than that at the other two sites (A_i and $HA2-HA1$). The water losses from the upper peat layer ($A2$) at the three sites were similar. Furthermore, the variations of $HA2-HA1$ could represent long-term trends of drainage characteristics

at each site. The drainage intensity at Site D clearly increased from 1983 to 2013, and the variations of drainage intensity at sites M (at the edge of the peat mining area) and U (in an unused area far from the drainage) were not as significant.

In the validations of the PTM based evaluation method, two types of GWT data were used. The simulation results both achieved the accuracy of less than a few centimeters. However, in the structure of PTM described above, the seasonal response of evapotranspiration and amount of soil moisture in unsaturated peat surface soils were not considered.

In the final part of this study, further improvement was made to the proposed method to incorporate the effects of evapotranspiration variations into the algorithm of PTM for more rational and accurate simulation. A new parameter named *ETr* (the ratio of evapotranspiration used to represent the effect of different vegetation cover on the actual evapotranspiration of the peat) was added and the simulation error was reduced by 17.6%, 23.4% and 30.1% for sites E, W and WB, respectively. Through the modification, the effects of discharge and evapotranspiration that occur at different heights of peat layers with different physical mechanisms are separated. Furthermore, the effects of improvement of simulation were obvious at the peaks and the depletion of the GWT fluctuation curve. This modification did not change the profile of the parameter variations.

In summary, this study proposed a new method based on Peatland Tank Model to quantify and to evaluate the groundwater table fluctuations in peatland. The operation of Peatland Tank Model simply requires time-series data of groundwater table and rainfall. The effectiveness of this method and its applicability for two types of groundwater table data were validated through simulations using the 29-year groundwater table

fluctuations in Gensekaen and Ochiai of Sarobetsu Mire, northern Hokkaido, Japan. The fluctuation patterns of groundwater table can be distinguished by using only few parameters. Further structural improvement of this model was made to incorporate the effects of evapotranspiration variations into the algorithm for more rational and accurate simulation. Better simulation accuracy was obtained by this perfection. Comprehensive analyses and discussions were provided for better understanding of this method. The proposed method possesses the merits of simple computational structure, small number of required measurements and high accuracy. It is very meaningful for the research in peatland hydrology, especially when computational complexity is concerned. This model can be expected to play an active role in the basic hydrological study of peatland.

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CHAPTER 1

General introduction

1.1 Peatland and hydrology

Peat is the incompletely decayed remains of the plants that grew on what was once the surface (Clymo *et al.* 1998). Formation of peat occurs in areas where water input is more than water output. Under such a waterlogged condition, the decomposition rate of plant material is lower than the production rate of vegetation, which leads to the peat accumulation. Classification of peatland is determined by two fundamental factors: source of nutrients and source of water. To be specific, bogs or ombrotrophic peatlands are dependent on precipitation for water and nutrient supply, whereas minerotrophic peatlands or fens rely on groundwater (Johnson and Dunham 1963). Bogs, also known as ombrogenous mires, are irrigated by precipitation only, and thus their plant communities are specialized for nutrient-poor conditions. Essentially, bogs have very shallow groundwater table because they occur in climates with precipitation excess, on flat or gently sloping ground, and with drainage impeded by low soil permeability (Ingram 1982).

The peat profile has been divided into two layers (Ingram 1978), namely, the catotelm and the acrotelm. The catotelm (anaerobic underlying layer) is typically 1m to 5m (or sometime even up to 10m) thick and consists of dead, partly decayed plant materials, which are perennially waterlogged. The catotelm usually shows less variation in hydraulic structure with depth (Chason and Siegel 1986). The more decomposed peat of the catotelm has smaller pores than peat in the acrotelm:

consequently hydraulic conductivity is lower because the flow path is more tortuous and frictional effects on flow are much greater (Price *et al.* 2003).

The acrotelm (aerobic upper layer) is a thin surface skin with a thickness of less than 1 m (Ivanov 1981; Lindsay 2010). It is mostly defined as the layer which encompasses the full range of water table fluctuations (Bragg 1982; Clymo 1984; Ingram 1978; Wheeler 1999). Its hydraulic structure changes rapidly with depth below the surface. Hydraulic conductivity decreases by up to 4 orders of magnitude over a distance of 50 cm (Boelter, 1965) and sometimes more (*e.g.* Hoag and Price 1995); and specific yield from 0.5 to 0.1 over the same range (Price 1992).

Peatlands are likely to be formed in regions with high precipitation excess, such as upland areas of the temperate and boreal zones or in lowland areas where shallow gradients. It is known that approximately 3% of the Earth's land surface is covered by peatlands (Page *et al.* 2011), which are mainly distributed in two climatic zones of boreal and subarctic zone (even arctic) and tropic zone (Schumann and Joosten 2008). Statistically, without taking the tropic zone into consideration, nearly one third of the total world pool of soil carbon is stored in peatlands located at boreal and subarctic zone. In recent years, peatlands have been recognized as providing the significant ecosystem services including biodiversity, carbon sequestration, water supply, hydrology adjustment, and recreation (Bonn *et al.* 2009).

With the aggravation of global warming, peatland ecosystem attracts more and more attentions. This is because peatland contains huge amount of carbon and plant remains (Gorham 1991; Yu *et al.* 2010) and has great impact on the global warming from the viewpoint of carbon release. The amount of carbon in peatlands is already next to the total amount of carbon in the atmosphere. Thus, the quantity of carbon in peatlands is

really huge and it can exacerbate the global warming if a substantial amount of carbon in peatlands is released into air.

One of the most important factors that affect the release of carbon in peatlands is the condition of peatland hydrology. In theory, the changes of hydrological conditions, such as the groundwater table drawdown, will affect the decomposition of peat and the release of greenhouse gases like CO₂ and methane. The relative position of water table within the peat ultimately controls the balance between peat accumulation and peat decomposition. Therefore, it affects the stability of peatland. Because of this, peat is very sensitive to changes in hydrology that may be brought about by climate or land use change (Holden *et al.* 2004). In recent years, human exploitation of peatland environments and changes in the climatic water budget can alter the hydrology of these environments and may result in many peatlands switching from a carbon sink to a carbon source (Aurela *et al.* 2001; Belyea and Malmer 2004). For instance, the anthropogenic disturbances include draining for agricultural development and forestry (Frolking *et al.* 2011; Holden *et al.* 2004), peat mining and harvesting (Mohammadighavam and Kløve 2014; Van Seters and Price 2001), peat fires (Page *et al.* 2002; Wösten *et al.* 2008). The self-reformation processes in peatlands also can change their hydrological conditions over time at different places, such as forming of natural ditches in peatland.

Peatland hydrology includes surface, near-surface moisture, position of the water table, and water flow movement (Dise *et al.* 1993; Moore and Roulet 1993). Peatland hydrology influences gas diffusion rates, redox status, availability and cycling of nutrient and species composition and diversity (Holden 2005b). It drives carbon sequestration and release processes, and is important for water resource management,

flooding and stream water quality. The hydrology determines plants growth, how peat stored and how peat decomposed. Therefore, attentions must be given to the studies of peatland hydrology in concern of the protection and maintenance of peatland ecosystem.

Intuitively, the hydrologic behavior of peatland can usually be expressed by the fluctuation of groundwater table. On one hand, low water table cause increased O₂ availability, and thus increase the vegetation productivity and the decomposition of peat soil. Then, pore space of peat will decrease. This will further lead to a low hydraulic conductivity. In addition, the decreasing pore space will result in the storage coefficient decrease. Consequently, the fluctuation of water table and run off will increase. On the other hand, high water tables tend to inhibit both soil decomposition and plant productivity; so gradual drying can result in increases in both CO₂ uptakes by plants and CO₂ emissions from decomposition. The larger water level fluctuations facilitate the growth of higher (trees, shrubs) and deeper (dwarf shrubs, grasses) rooting vegetation, which affects the hydraulic peat properties through physical cracking (wind) and perforation. The taller vegetation may further enhance evapotranspiration, leading to lower water levels etc. (Schumann and Joosten 2008).

In mires, a small change of a few centimeters in the average water level may lead to a significant change in the vegetation community and may strongly affect the accumulation and mineralization rates of peat, the process of carbon sequestration and the other associated properties. Moreover, the afore-mentioned disturbances will change the hydraulic properties (porosity, storage coefficient, hydraulic conductivity) of peat. They may further decrease the peatland's capacities for water storage and regulation (Schumann and Joosten 2008). Therefore, the investigation of hydrological

conditions of peatlands, and qualitative and quantitative evaluation of hydrological conditions of peatland are necessary for the reservation and proper usage of peatland.

1.2 Research and application of peatland hydrological model

Although different methodologies have been proposed to facilitate the research work in peatland hydrology, many researchers are found to be especially interested in the usage of hydrological models. The hydrological models are generally simple, convenient, efficient and accurate. Therefore, due to their attractive features, extensive research work has been carried out on development and application of appropriate hydrological models for peatland.

Researchers have proposed a variety of hydrological models ranging from conceptual model to detailed mathematical model. For instance, a landscape modeling framework was proposed by Sulman *et al.* (2013) to study the effects of mean water table variations on the peat decomposition and plant community. The conventional LANDIS-II model was modified by incorporating the simulation of hydrological effects. In this way, the relationship between landscape carbon storage and water table decrease was found by using the proposed coupled modeling framework (Sulman *et al.* 2013). Intrinsically, the landscape modeling framework is a combination of ecological and hydrological models. It is not especially designed to provide detailed characteristics of hydrological conditions of peatland. Thus, it is not directly applicable to some research studies that require accurate and in-depth modeling of peatland hydrological conditions. Ballard *et al.* (2011) proposed a three-dimensional hydrological model, which combined four one-dimensional models, for drained blanket peatland. The model is physics-based and focuses on the exploration of water

flow and hydrological processes. A good model performance is reported for wet periods based on case study. This model serves as potential guidance for the management of water budget in a catchment scale. Despite of its merits, this model is idealized to exclude the unsaturated zone of blanket peatland. Such an idealization may not be valid under some situations. Furthermore, the computational complexity of this model is high and its operation requires many theoretical assumptions.

Research studies have also been carried out on the peatland hydrological modeling by considering the effects on both saturated and unsaturated zones. For instance, in 2010, the SIMGRO model (Querner *et al.* 2010) was developed to model the peatland hydrology. The model is capable of simulating the groundwater flow and surface water flow under changing hydrological conditions. Practical case studies have shown the satisfactory performance on the estimation of discharges and groundwater levels by using this model. Nevertheless, measurements of many physical variables are necessary for the application of this model. Also, its computational complexity is high and the guideline of model parameter tuning is not provided.

In addition, hydrological models based on specific structure features of peatland have also been developed. One example is the acrotelm-catotelm model (Holden and Burt, 2003) , which is evaluated for its application on the hydrological studies of blanket peat. Peatland is considered as a two-layer system, consisting of the acrotelm (thin, aerobic upper layer) and catotelm (thick, anaerobic underlying layer) (Clymo 1984; Ingram 1978; Ivanov 1981). For a bog, the boundary between the two layers is approximately the mean value of depths of the lowest summer water table (Clymo 1984). The zone of GWT fluctuation is nearly equal to the width of acrotelm. Thus, the shallow GWT change affects photosynthetic production of living plants and decomposition of litter

and peat in both the acrotelm and catotelm. The acrotelm-catotelm model is proved to be effective in quantifying different factors on the controlling of runoff generation from blanket peat, in monitoring the spatial and temporal pattern of runoff production and in examining the infiltration process. It is advantageous for the analyses of many hydrological behaviors in blanket peat such as the amount and direction of runoff from the hillside. However, this model requires a large number of input variables and complicated computations. This increases the cost of study and the computational burden. Moreover, the acrotelm-catotelm model may not be suitable for the studies of some types of peatland.

Three-dimensional (3D) groundwater models such as MODFLOW have been developed (McDonald and Harbaugh 1984). MODFLOW is regarded as an international standard for simulation and prediction of groundwater conditions and groundwater/surface-water interactions. Based on MODFLOW, several new models have been established to examine GWT variations in bogs (Bradley 1996) and the water budget in peatland (Reeve *et al.* 2001). A transient two-dimensional (2D) saturated-unsaturated model was developed by Freeze (Freeze 1971) to investigate relationships among infiltration rates, GWT increase, and base flow hydrographs (Zhou and Li 2011).

In general, the aforementioned 2D and 3D groundwater flow models were developed to simulate water flow in wetland or peatland on a catchment scale. However, the hydrological independence of bogs is clearly different from other types of peatland. Specifically, a bog is fed by precipitation rather than inflow from the surrounding watershed. Except for the small upward supply of deep groundwater to the peat layer, precipitation is the only water input to bogs. Outflow from the bog is discharged to

surrounding topographically lower areas and infiltrations. The hydrologic behavior of the bog is relatively independent of the surrounding catchment.

As mentioned before, an insightful evaluation of the hydrological conditions of groundwater system is usually the prerequisite for the protection and management of such a system. Of course, there are many ways to implement the evaluation in either qualitative or quantitative manners. Nevertheless, it is widely accepted that mathematical modeling is one of the most effective evaluation methods for the groundwater hydrology. This is because models can usually give people intuitive perceptions and mathematical analyses are concrete and instructive. In view of this, a substantial amount of research work has been carried out to investigate the appropriate models for the groundwater hydrology. For instance, a coupled hydrological/hydraulic model was developed to study the effects of climate changes on wetlands! (Thompson *et al.* 2009). It simulated the conditions of groundwater in wetlands, such as groundwater depth and ditch water level. Also, it provided the analysis of floods and a number of ecological implications associated with the climate change upon the hydrology of wetlands. Although it contributes to the study of vulnerability of wetlands to climate changes, the proposed method may not be directly applicable to the hydrology of peatlands. More research articles were published to assess the impacts of groundwater exploitation, groundwater management and climate changes. In 2009, Lucila Candela and his colleagues investigated the effects of climate change on groundwater resources recharge and the impact of combined climate and management scenarios on the hydrogeological system. They coupled the downscaled outputs (temperature and precipitation) of a general circulation model (GCM) with a groundwater model for the purpose of estimation. Consequently, the good estimation

accuracy was obtained. Nonetheless, the proposed model is mathematically complicated and requires the measurements of many inputs. Also, it is not particularly focusing on the study of peatland hydrology. Another paper was published in 2014 (Les Landes 2014) with the aim of assessing and comparing the effects of groundwater abstraction and climate change on groundwater-fed wetlands. A groundwater model was developed to represent surface-subsurface groundwater interactions. Again, it was coupled with a few downscaled outputs from 14 GCM. Based on the model, numerical analyses were carried out and instructive suggestions were given to mitigate the impacts of climate change and groundwater abstraction. This paper had considered the characteristics of peat, especially the peat exploitation. However, it is still associated with the problems of high complexity and the measurements of many variables.

In this study, we demonstrate the applicability of the peatland tank model (PTM) (Umeda 1980) for simulating fluctuations in the shallow GWT of a peatland and discuss its practical use. This model is used to simulate GWT fluctuations at one single spot at a bog site by continuously measured rainfall and GWT data. It cannot represent multi-dimensional water movement or the function of hydrological factors. However, this model can express the difference in GWT fluctuation patterns by location or time using only two or three parameters. PTM calculation does not require a series of parameters representing peat properties and hydraulic characteristics such as hydraulic conductivity, specific storage, specific yield and bulk density. Further, this model does not need to deal with geographical information such as topographic information, soil type and land use.

When researchers start investigating peatland hydrology, GWT and rainfall measurements are so basic and essential that in many cases, they have already been

considered in many locations. Even in cases where only GWT data has been measured, PTM can simulate GWT fluctuation patterns if continuous rainfall data is available for a neighbouring weather station.

Simulating the shallow GWT fluctuations using PTM requires less operational arrangement and its implementation is easier than the aforementioned hydrological models. The operational platform for PTM is a program using Microsoft Excel's macro function. The calculation can be rapid. The simulation result using PTM can attain an accuracy of less than a few centimetres, which is crucial for evaluating the condition for bog vegetation. This is important because shallow GWT variations of a few centimetres may affect plant growth conditions and peat accumulation circumstances.

1.3 Research objectives

This study aims to show the practical usage of PTM and groundwater table data in various forms for evaluating the GWT fluctuation patterns and hydrological conditions of peatland. To be specific, the GWT data with reference to the elevation above sea level and the GWT data measured without any reference benchmark are used in the simulations and analyses of this study. In view of the significance of peatland hydrological conditions in the activities of peatland management and protection, research attentions should be given to the evaluation of essential characteristics of peatland hydrology. As it is widely acknowledged, the fluctuation of groundwater table (GWT) data is an effective indicator of the behaviour of peatland hydrology. Therefore, this study investigates the dynamics of peatland hydrology by examining the fluctuations of GWT. A simple but effective evaluation method is proposed in this study for the simulation of GWT fluctuations in peatland. It is derived on the basis of

peatland tank model (PTM) and provides mathematical simplicity and good simulation accuracy. Furthermore, the proposed method only requires the measurement of GWT and is compatible to GWT data in various forms. To be specific, both the GWT data with reference to the elevation above sea level and the GWT data measured without any reference benchmark can be used by the proposed method for simulations. Analysis of the simulation results provides in-depth understanding of the behaviour of peatland hydrology.

In order to evaluate the special differences and temporal variations in the patterns of groundwater fluctuations of peatland, the proposed PTM is applied to practical case studies. To provide a guideline for proper usage of the proposed method and to verify its veracity, some case studies are presented in this thesis based on the practical GWT data (29 years' GWT samples in Sarobetsu Mire, Northern Japan). In these case studies, detailed discussions are made on the evaluation of differences and temporal variations of the groundwater fluctuation patterns of peatland.

To yield a better understanding of the proposed PTM, discussions are made on the meaning and function of each parameter used in PTM. It is noteworthy that several parameters are used in the proposed PTM based method. Instructions on the definition, physical meaning and function of each parameter are given in this thesis to yield a better understanding of the proposed method. The basic principles of simulation tuning by varying these parameters are introduced. Also, the effects of parameter variations on the simulation accuracy are discussed. Concrete simulation results are provided to support the arguments. In addition, the usefulness and effectiveness of PTM on the simulation of shallow peatland GWT are summarized.

To improve the simulation accuracy of PTM and to ameliorate its structure,

evapotranspiration variations are incorporated into the original model. Detailed analyses are provided on the effects of incorporation of evapotranspiration. In concern of the integrity and accuracy improvement of the proposed evaluation method, research efforts are made to incorporate the effects of evapotranspiration variations into the original model. Explicit mathematical expressions and explanations are provided for this modification. Moreover, simulations are carried out to investigate the effects of evapotranspiration incorporation and the results are compared with those obtained by using the original model. Discussions are made based on the comparisons and conclusions are given.

CHAPTER 2

Evaluation of hydrological environment in Genseikaen of Sarobetsu

Mire, northern Hokkaido, Japan

2.1 Introduction

Monitoring the shallow groundwater table (GWT) is indispensable for detecting changes in the hydrological conditions of a peatland affected by various natural and anthropogenic disturbances. In this study, the GWT is continuously measured from 1983 to 2013 in a bog called Genseikaen of Sarobetsu Mire located in Hokkaido, Japan. The GWT data used in this chapter is represented as absolute height above sea level. This is meaningful for investigating the peat growth and subsidence of peatland.

In this chapter, the method for quantifying and evaluating the shallow GWT fluctuation of a bog by applying Peatland Tank Model (PTM) (Umeda 1980) will be demonstrated. The theory, necessary inputs data of the PTM will be introduced and the simulation principle will be explored. The meaning of PTM's parameters will be discussed for describing the fluctuation patterns of the GWT. The variations of PTM's parameters will be interpreted for understanding the hydrological alteration at a spatial and temporal scale.

2.2 Methods

2.2.1 Overview of Peatland Tank Model

Peatland Tank Model (PTM) is a hydrological model for simulating fluctuations in the shallow groundwater table (GWT) of a peatland. PTM is developed after having a

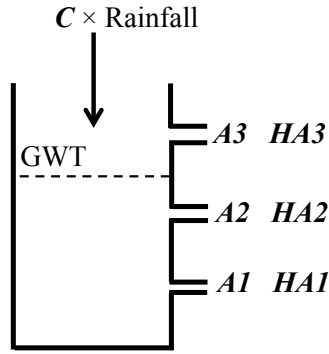


Fig. 2-1 Peatland Tank Model

hint from Sugawara's tank model (1972), which simulates the river outflow by the discharge from a tank. However, the PTM supposes the water level of a tank as the GWT in peatland. As indicated by its name, the peatland hydrological system is analogous to a water storage tank (Fig. 2-1). The GWT fluctuations of a peatland can be represented by the variations in water levels of a tank. For instance, the GWT of a bog is increased mainly by rainfall, because there are almost no other water inputs from the surrounding environment so rainfall is the sole inputs to the bog. In contrast, the GWT is reduced by water outputs because of evapotranspiration (ET) and outflow from the bog to surrounding areas. This is similar to variations in the water level of a tank, in which increases and decreases of water levels are caused by input from the top of the tank and output to plugholes, respectively. This is illustrated in Fig. 2-1 where plugholes are on the tank sidewall.

In theory, the PTM can be characterized by Equations 2-1 and 2-2.

$$GWT_n = GWT_{n-1} + C \times R_n - \left(\sum_{i=1}^3 Q A i_{n-1} \right) \quad (2-1)$$

$$Q A i_{n-1} = A i \times (GWT_{n-1} - H A i) \quad (2-2)$$

Here, GWT_n and GWT_{n-1} represent GWT at time n and $n-1$, respectively. C is the coefficient of GWT increase owing to rain. R_n is the amount of rainfall during time period $(n-1)$ to n . QAI_{n-1} is the amount of groundwater drawdown from the i th plughole (i : number of plugholes, $i = 1-3$) during period $(n-1)$ to n . Coefficients Ai ($0 \leq Ai \leq 1$) and HAI are the size and height of the i th plughole, respectively. It is noted that C and Ai are unit less, and other abovementioned parameters and variables are in centimetres. Altogether, the prototype of the PTM has seven parameters (C , $A1$, $A2$, $A3$, HAI , $HA2$ and $HA3$). The way to reduce the number of parameters will be shown later in this paper. The PTM estimates of GWT are based on a sample period of either 1 day or 1 hour. Here, we reveal a model using the latter period, which improves simulation accuracy of the GWT fluctuations.

2.2.2 Meaning of the parameters in PTM

The amount of rainfall occurred during a unit time can increase the GWT. To demonstrate this process, coefficient C is used. It can be interpreted as the ratio between GWT increase and rainfall amount, and represents the magnitude of GWT increase in response to rainfall in a peatland. A large value for C generally indicates lack of effective porosity for water storage in peat (Umeda and Inoue 1985). In PTM computation, the amplitude of GWT increase ($C \times R$) could be adjusted by changing C (cf. Equation 2-1).

The amplitude of GWT drawdown (QAI) can be similarly regulated by modifying the size (Ai) or height (HAI) of each plughole (cf. Equation 2-2). For appropriate modeling of the water loss in a peatland, discharge and evapotranspiration (ET) must be considered. In the present study, basic discharge from the peatland and ET from plant

and peat were incorporated into the water loss from the lowest plughole. Consequently, parameter $A1$ can represent the basic and relatively constant water loss from the peat layer above $HA1$. Parameters $A2$ and $A3$ also contribute to water loss from the layer above $HA2$ and $HA3$, respectively. More rapid water loss at the shallow surface layer of peat is characterized by using $A2$ and $A3$. The response of ET in various seasons cannot be analytically expressed in this model unless a new parameter is introduced for ET. This will be considered in Chapter 4.

2.2.3 Necessary data for computing PTM

Beside the aforementioned seven parameters, two types of data are needed for actual PTM computations. The first is an initial value for GWT data, which is used to initialize the computation of PTM. The second is the sequence of observed hourly rainfall, which is used during the entire PTM computation. To evaluate the computation, continuously recorded GWT data are also necessary.

2.2.4 Reducing the number of PTM parameters

As the description aforementioned, there are seven parameters (C , $A1$, $A2$, $A3$, $HA1$, $HA2$, and $HA3$) in the original PTM that must be properly determined to accord the estimated GWT with the observed GWT. However, selecting the appropriate values for all the parameters is not a simple task because it is difficult to simultaneously adjust all the seven parameters. Furthermore, the determination of parameters is meaningless without setting up explicit principles, which help to distinguish the contribution of each parameter. To be specific, a smaller HAi or a larger Ai can generate the same effect of increasing water loss intensity; however, the quantitative contribution of each

parameter is different. This means that the contribution of each parameter becomes ambiguous if both HA_i and A_i are simultaneously changed.

On the basis of our experience of PTM's computation and analyses for the simulation results, the number of parameters can be reduced into four, three, or even two. Four simulation cases (Case 1, Case 2, Case 3 and Case 4; Table 2-1) have been executed and following four rules (footnote in Table 2-1) have been set up. Rule *1 fixed the vertical distances (VDs) between two adjacent plugholes as 40 cm ($HA_2 - HA_1$) and 10 cm ($HA_3 - HA_2$). But if $HA_2 + 10$ cm is higher than ground surface elevation (GSE), the value of HA_3 is equal to the GSE. Rule *2 set the value for HA_2 (height of the middle plughole) as upper tertile of the observed GWT data within the calculation period. The upper tertile of GWT data was determined by the following steps. In the first step, all observed GWT data within the calculation period at each site were sorted numerically, in descending order. This set should include every datum, even if there were overlaps. Then, the value found one third of the way down from the maximum value of the organized data set is defined as the upper tertile. Rule *3 determined the size of two plugholes (A_1 and A_2) as constant values, and kept the VD of the high two plugholes same as Rule *1. Rule *4 fixed the size of the highest plughole A_3 as 1 in all simulation cases. They are conducive to simplify the operation of PTM, determination of the parameters, distinguish the contribution of each parameter and reduce the number of parameters.

Table 2-1. Simulation cases

Case	Manipulated Parameters	Fixed or Automatically Determined Parameters	Rules
1	$C, A1, A2, HA2$	$A3, HA1, HA3$	*1, *4
2	$C, A1, A2, HA2$	$A3, HA1, HA3$	*1, *4
3	$C, A1, A2$	$A3, HA1, HA2, HA3$	*1, *2, *4
4	$C, HA1$	$A1, A2, A3, HA2, HA3$	*2, *3, *4

Rule *1: $HA1 = HA2 - 40\text{cm}$, $HA3 = HA2 + 10\text{ cm}$ or $HA3 = \text{GSE}$ (if $(HA2 + 10\text{ cm}) > \text{GSE}$, GSE: ground surface elevation).

Rule *2: $HA2$ equals the value of upper tertile of GWT data that calculated by the following steps. In the first step, all observed GWT data within the calculation period at each site were sorted numerically, in descending order. This set should include every datum, even if there were overlaps. Then, the value found one third of the way down from the maximum value of the organized data set is defined as the upper tertile.

Rule *3: $A1 = 0.0002$, $A2 = 0.02$, $HA3 = HA2 + 10\text{ cm}$ or $HA3 = \text{GSE}$ (if $(HA2 + 10\text{ cm}) > \text{GSE}$).

Rule *4: In all cases, $A3 = 1$.

In Case 1, the 30 years' PTM calculations were all performed within the same period from 1 July to 30 September (warm period without snow coverage and snow melt). However, the starting day (1 July) in each year might be rainy day, just after a rain event or rain-free day and their effects on GWT simulation may be different. To consider the effect, the starting point of calculation have been fine modified to rain-free day when 1 July is a rainy day or a day just after rain event. Based on the comparison of simulation results, the calculation initiation on a rain-free day can produce a better-fit and smaller error than that on a rainy day. Thus, the calculations were performed from July to September and started from a rain-free day in Cases 2, 3 and 4.

The VDs between two adjacent plugholes were kept constant (Rule *1) in Case 1 to Case 3. The value for $HA2$ (height of the middle plughole) was chosen to be equal to the upper tertile (Rule *2) in Case 3. By setting the height of a middle plughole within

the range of GWT fluctuations, a faster GWT decrease during high GWT conditions can be generated. The values for VDs between two adjacent plugholes (10 cm and 40 cm) and the $HA2$ value (the upper tertile) are the empirical values based on the PTM's computations.

In Case 1 and 2, the upper tertile was rounded from decimals to integers, and then it have been as the reference value for $HA2$. The $HA2$ value was adjusted by changing the integer bits of the reference value to obtain smaller simulation error in case 1 and 2. By comparing the results of Case 2 and Case 3, it can be known that the adjustment for $HA2$ value did not produce smaller calculation error significantly ($P > 0.05$). Thus, The $HA2$ value was chosen to be equal to the upper tertile in later simulation cases (Case 3 and Case 4).

When the value for $HA2$ was determined, the value for $HA1$ and $HA3$ were automatically determined because the VDs were kept constant in Case 1 to Case 3. As a result, the number of parameter HAi could be reduced. It is noteworthy that when the height of the highest plughole ($HA3 = HA2 + 10$ cm) was much higher than GSE, $HA3$ was kept equivalent to the ground surface elevation ($HA3 = \text{GSE}$). This is regarded as a special case for determining the $HA3$ value.

In Case 4, the size of each plughole was predetermined by Rule *3. The determination of the heights of the upper two plugholes ($HA2$ and $HA3$) is the same as Case 3. In Case 3, the sizes of all plugholes (Ai) were manipulated and the heights of all plugholes (HAi) were maintained constant. But, in Case 4 the height of the lowest plughole $HA1$ (i.e. the vertical distance between the two lower outlet plugholes $HA2-HA1$ (VD_{21})) was manipulated and the sizes of all plugholes (Ai) were kept constant. This arrangement distinguished the different contributions of HAi and Ai .

In all cases, the value for $A3$ was fixed at 1 by Rule *4. This is because during heavy rain, the GWT may rise above the height of $HA3$ or the peat surface. Under such circumstances, rapid discharge can occur within a short period. To illustrate the effects of such discharges, $A3$ was considered to be equal to 1.

Thus, using these simulation cases and rules shown in Table 2-1, the number of parameters in PTM was reduced from the original seven (C , $A1$, $A2$, $A3$, $HA1$, $HA2$, and $HA3$) to four (Cases 1 and 2: C , $A1$, $A2$ and $HA2$), three (Case 3: C , $A1$ and $A2$) or two (Case 4: C and $HA1$).

2.2.5 Parameter manipulation and accuracy evaluation

The manipulated parameters for each simulation case (Table 2-1) were determined using the trial and error method. Parameters C was adjusted by changing the digit after the first decimal, $A1$ was adjusted by changing the digit after the fourth decimal, $A2$ by changing the digit after the second decimal and HAi was adjusted by changing integer bits.

These parameters were repeatedly adjusted until the optimum simulation result was attained, for which the Chi-square error (CHI) and absolute error (AE) were minimized, and correlation coefficient (r) was maximized. The accuracy of the simulation results was evaluated by comparing the observed and computed GWT.

2.2.6 Case study for PTM application

To demonstrate the PTM applicability for spatial variability and temporal change for a hydrological situation in peatland, we carried out a series of case studies. In these studies, different types of vegetation over relatively small areas at the

observation sites in a single peatland were included. At each site, GWT were observed continuously yearly from 1983 to 2013.

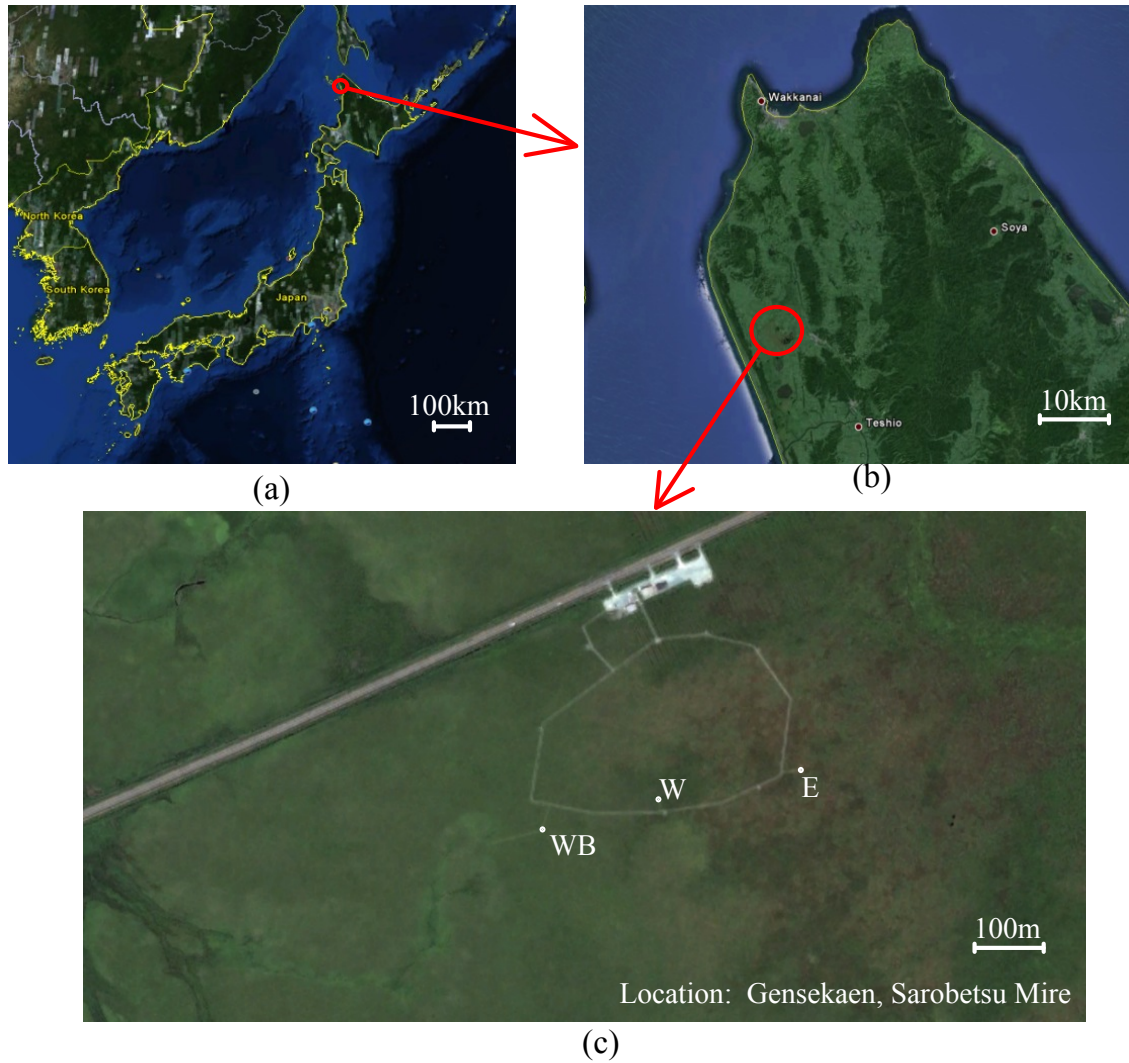


Fig. 2-2 Genseikaen, Sarobetsu Mire locate in Hokkaido, Norethern Japan

(a):Hokkaido in Japan; (b): Sarobetsu Mire Area

(c): observation sites (white points): E, W, WB in Genseikaen.

a. Location and climatic conditions of the study area

GWT and rainfall were observed continuously in an area of the Sarobetsu Mire from 1983 to 2013. This mire is in northern Hokkaido, Japan (approximately 45°5'N, 141°1'E), and its original total area was approximately 14,600 ha (Hokkaido Development Agency 1963) (Fig. 2-2). Part of this mire was transformed into grassland for dairy farming in the early 1980s, and the remaining peatland has been preserved as part of the National Park of Rishiri Rebun Sarobetsu since 1974. Annual average temperature of this area is approximately 6.1 °C, from −6.5 °C in February to 19.6 °C in August; annual average precipitation is 1,073 mm (average of 1981 to 2010, Japan Meteorological Agency). Snowfall accumulated during winter season accounts for approximately one-third of the annual precipitation. On average, the warm period without snow coverage lasts from mid-April to late October.

b. General characteristics of the study area

The topography of Sarobetsu Mire is generally very low and flat. Peat depth reaches 6 m (Hokkaido Development Agency 1963). A bog has formed in the center of Sarobetsu Mire, surrounded by fens and transitional peatland. The main drainage river for the peatland is Sarobetsu River, which flowing from north to south. The Sarobetsu River finally joins Teshio River as its trunk stream. On the banks of the Sarobetsu River, naturally formed narrow ditches cover the surface of the marginal zones (lagg) connecting the riverbanks. These narrow ditches function as natural drainage systems for the peatland (Okada 2009). Beside these ditches, part of the Sarobetsu River and some of its branches have been converted to artificial drainage channels over the last century. These have influenced the drainage condition of the peatland. Moreover, the side ditches of a road intersecting the central part of the mire

also appears to somewhat affect the hydrological conditions of the peatland. In the eastern area of the bog, peat mining occurred from 1970 to 2002. Invasion of *Sasa*, a plant preferring drier conditions, has become problematic because of drainage effects through natural narrow ditches, the river system, newly developed drainage channels and road ditches (Fujimura *et al.* 2012). Because the *Sasa* has spread from west to east through certain parts of the mire, it threatens the native *Sphagnum* vegetation, which has been the dominant species there. The extent of *Sasa* communities has increased by 15.8 % from 6.60 km² in 1977 to 7.64 km² in 2003 (Fujimura *et al.* 2012). Consequently, the problem of *Sasa* invasion should be considered for the conservation of mire (Fujita *et al.* 2003).

c. Observation site details

Three observation sites were constructed along the boardwalk of the mire, from east to west (Fig. 2-2): Site E (*Sphagnum*-dominant community, 45°06'16.4"N, 141°41'15.9"E), Site W (front line of *Sasa* community invasion toward *Sphagnum*-dominated bog vegetation, 45°06'15.4"N, 141°41'07.6"E) and Site WB (*Sasa*-dominant community, 45°06'14.2"N, 141°40'59.4"E). The *Sphagnum* community at Site E comprised *Sphagnum papillosum* Lindb., *Sphagnum magellanicum* Brid. and *Carex middendorffii*. The *Sasa* community at Site WB is composed of *Sasa palmata*, *Myrica gale* L. var. *tomentosa* C.D.C. and *Ilex crenata* Thunb. var. *radicans* (Nakai ex H. Hara) Murai (Fujimura *et al.* 2012).

The average ground surface elevation (GSE) at sites E, W, and WB were 6.08 m, 5.97 m and 5.83 m, respectively. However, changes in GSE are not addressed in this study for the following reasons. First, the peatland surface changes or oscillates as GWT fluctuates (Fritz *et al.* 2008; Lindsay 2010). Second, it is difficult to keep the

measurement location unchanged on the peat surface for every measurement. Finally, surface elevation could not be accurately measured because of the unevenness and roughness of the peat surface. In this study, the GWT height is expressed using the height above sea level and not using the relative height or depth from the peat surface. The distance between Site E and W was 190 m and that between Site W and WB is 170 m. Part of the upstream borders of the natural narrow ditches were approximately 180 m west of WB. Peat thickness was enumerated as 7.14 m for Site E and 5.98 m for Site WB. In addition, surface peats at Site E and W were very raw and undecomposed, whereas that at Site WB, the surface peat was slightly decomposed.

d. Measurements

There are long-term observations of GWT monitoring and rainfall measurements from 1983 to 2013 (except for 1986 and 1990). These observations covered several months of each year, with the minimum period from July to September.

Rainfall using in this study was measured at two locations. One was at Site E and the other (as a backup) at the starting point of the boardwalk nears the former Visitor's Center of Sarobetsu, Genseikaen area. Tipping-bucket rain gauges (0.5 mm/tip and 0.1 mm/tip; Ikeda Keiki Co., Ltd., Tokyo, Japan) were used. Missing rainfall data were substituted with data from the Toyotomi station (6.1 km east of the study area) of the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Metrological Agency.

GWT was automatically recorded at observation wells or piezometer pipes installed at sites E, W, and WB. There were some missing observations at sites E and W. The lack of observations for Site E is in 1986 and 1990, for Site W is in 1985, 1986, 1990 and 2006. For site WB, GWT observation began in 1991.

Float-type water level recorders (Suiken 62 Type Nakaasa, self-made float-and-counterweight balance type water level recorder with potentiometer) set in the observation wells were used for GWT measurements in earlier periods. The maximum well depth was 0.5 m. The well wall was bare or generally protected by perforated PVC pipes (its diameter is approximately 30 cm) placed along its depth. After around 2002, the float-type water level recorder was replaced by pressure sensors installed in the piezometer pipes. Several types of water level sensors (with recorders) were used (miniTroll, In-Situ Inc; WL16, Global Water; DL/N70, STS and S&DLmini, Oyo Chishitsu). Sensors were installed at depths below the expected minimum GWT in each perforated PVC pipe of inner diameter of 3 to 5 cm.

A level survey for all installed piezometer pipes was conducted along the boardwalk using a laser level (Nikon AL-3 Electronic Level System) once or twice per year from 1983 to 2013. A benchmark on the deep foundation pile installed by the Hokkaido Development Bureau was used to investigate the reference height above sea level. Manual measurements of ground water depth (distance between the top of pipe and ground water depth) were also conducted several times per year, using a water table detector (Million Rope Water Level Measure, RWL50M, Yamayo Measuring Tools Co., Ltd, Tokyo, Japan). The distance between the pipe head and ground surface was also manually measured. Based on the level survey, the elevation of pipe head was obtained. Then, the elevation of GWT and ground surface could be calculated. By this way, continuous fluctuations of GWT (absolute height above sea level) were acquired.

2.2.7 Analysis method of simulation results

The computations were performed for each observation site to simulate the GWT fluctuations. The annual simulation result was obtained for all three sites. Consequently, there are several sets of each parameter at each site (Site E: 29 sets, Site W: 24 sets and Site WB: 21 sets). Firstly, the set for each parameter was compared by site and examined using one-way analysis of variance (ANOVA). The ANOVA significance levels were set to 0.05 and 0.01. Secondly, based on the 29 years of GWT observations at each site, the long-term variation trend of each parameter was evaluated by using the coefficient of determination (R^2). Variations of each parameter were examined with respect to the GWT data and rain events. Characteristic values for the GWT data were average, minimum and maximum GWT. Characteristic values for rain events, such as the total amount of rainfall, total duration of rain events, rainfall intensity and longest rain-free days, were calculated. Multiple regression analyses were conducted to obtain the association relationship between these parameters and characteristic values of rain events and GWT data. All statistical tests were conducted using SPSS 16.0 statistical software (SPSS Inc., Chicago. IL, USA).

2.3 Results and discussion

2.3.1 Description of observed GWT fluctuations

Figure 2-3 shows the rainfall and the observed GWT data from 1983 to 2013. Total rainfall from 1 July to 30 September varied from 170.0 mm (1993) to 583.8 mm (1999), and the average was 334.0 mm (Fig. 2-3a). The GWT data (absolute height above sea level) at three sites show different variations (Fig. 2-3b, c, and d). The

GWT at Site WB fluctuated in lower elevation range than sites E and W and it is because the GSE at Site WB is the lowest. The GWT fluctuation range (FR) of three sites showed in Figure 2-4. At sites E and W, the difference of FR is not significant ($P > 0.05$) but FR at Site WB was substantially wider than those at sites E and W ($P < 0.01$). During the last 29 years of observation, the average FR (from July to September) of GWT at sites E and W were 16.5 cm. In contrast, the average FR at Site W was 30.1 cm.

2.3.2 Effect comparison for simulation cases

Four simulation cases (Table 2-1) were conducted to simulate the GWT fluctuations of Genseikaen of Sarobetsu Mire. The average errors are shown in Table 2-2.

In terms of calculation errors (CHI and AE) and simulation effect (r), the simulation by Case 2 is better than Case 1 at all three sites. It indicates that the calculation starting from a rain-free days can generate smaller errors and better fits. Thus, in subsequent simulation cases (Case 3 and Case 4), the calculation of each year was started from a rain-free day that is same as Case 2. Between Case 2 and Case 3, the errors and simulation effect during the last 30 years at each site were similar (even if the average errors of Case 2 are smaller than Case 3), and their simulation results (i.e. the values of the parameters C , $A1$ and $A2$) were almost the same and did not show significant difference ($P > 0.05$). Thus, the determination for $HA2$ by Rule *2 is considered easier and reasonable.

Through the experimental simulation by Case 1 and Case 2, the rules for determining the calculation-starting day and the height of plughole become definite.

The number of the manipulated parameters in Case 3 was reduced from original seven to three (C , $A1$, $A2$) and the parameters in Case 4 was reduced to two (C , HAI). Comparing Case 3 and Case 4, the errors of Case 4 are larger than Case 3. In this study, we mainly discuss the results by simulation Case 3 and Case 4.

2.3.3 The best and worst simulation results

The best (minimum error) and worst (maximum error) simulation results using PTM at each site are shown in Figure 2-5 (Case 3) and Figure 2-6 (Case 4). In both cases, AE of the best simulation results were < 1.0 cm, except the result at Site WB in 2009 by Case 4 (AE = 1.10 cm). For the worst simulation results, which were at sites E and W, AE were < 1.6 cm, and at Site WB, AE were < 3.4 cm in both cases. On average, AE of both cases at sites E and W were all < 1.0 cm (Table 2-2). The average AE at Site WB was < 1.9 cm for Case 3 and < 2.2 cm for Case 4.

The errors in the simulation results for PTM were mainly caused by the restrictions of the model. In practice, PTM cannot express the seasonal differences in ET and the amount and variation of soil moisture in an unsaturated surface peat layer. However, it is noted that such restrictions do not affect the simulation accuracy. Despite these restrictions, the simulation results for GWT fluctuations using PTM can still be accurate enough with very small AEs that were < 3.5 cm. In most cases, AEs were < 1.0 cm.

In both cases, results of Site WB were the worst among all three sites (Table 2-2). This can be briefly explained by the slow response of GWT to rainfall and ET at Site WB because the unsaturated zone of surface peat at Site WB was thicker than those at sites E and W. By comparing the two cases, we show that the verification was

simplified in Case 4 because the number of parameters in Case 4 was less than in Case 3. In contrast, fewer parameters caused larger simulation errors (Table 2-2). Thus, Case 4 is appropriate for simulations where high accuracy is not required but less computational intensity is desired.

All results by Case 3 and Case 4 at three sites are shown in the Appendix Figure 1. The annual result of each site (rank) by each simulation case (row) is shown in one page. The main y-axis of each figure is the GWT (cm) and the secondary y-axis of each figure is the rainfall (mm/hour) during calculation period. The x-axis is the date (from 1 July to 9 October). All parameter values and the errors in Case 3 and Case 4 are shown in Appendix Table1, 2, 6 and 7.

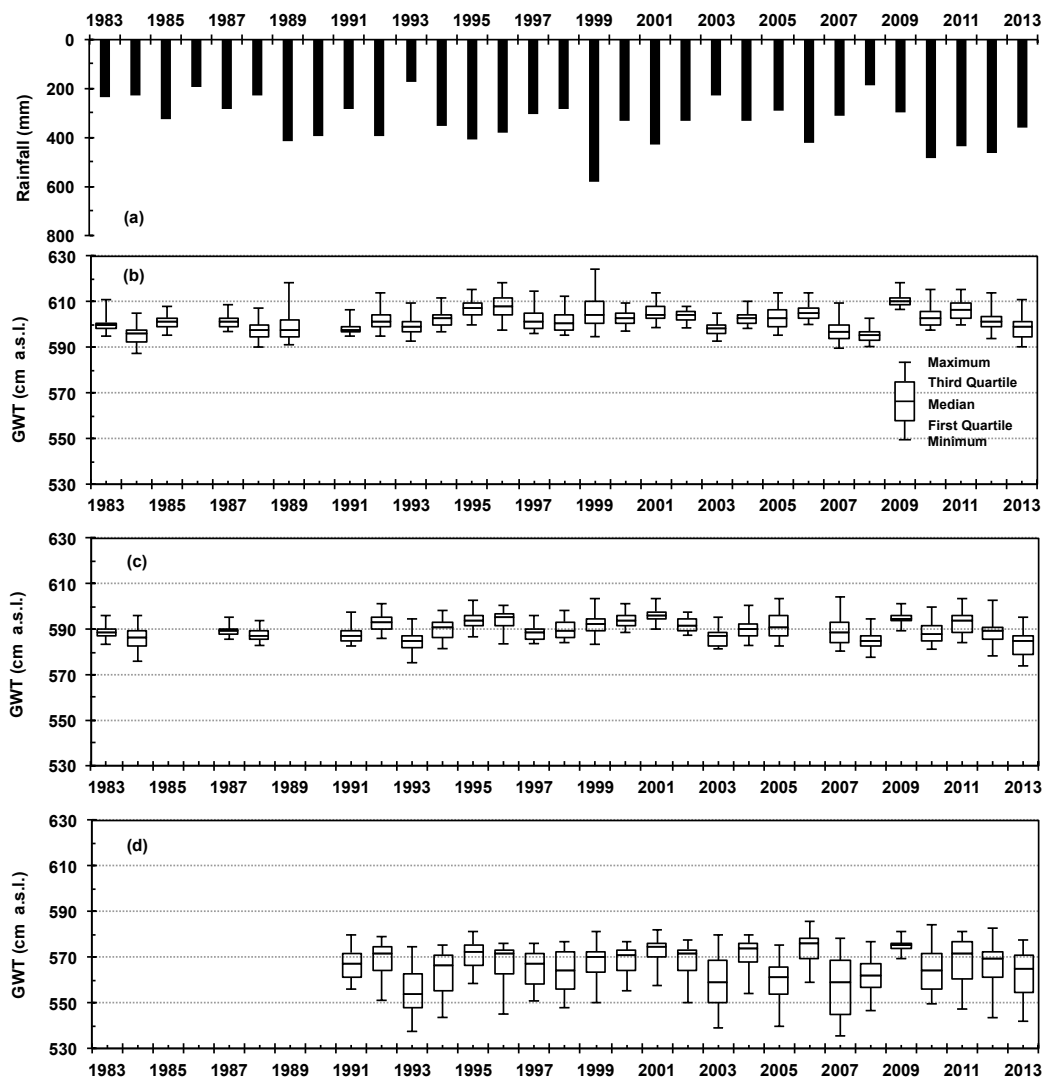


Fig. 2-3 Characteristics of observed GWT data at each site: (a) total rainfall from 1 July through 30 September; (b) range of observed GWT data at Sites E, (c) W, and (d) WB. Maximum, third quartile, median, first quartile and minimum values for GWT are expressed from top to bottom of each box in box plots b, c and d. No box indicates missing data. a.s.l.: above sea level.

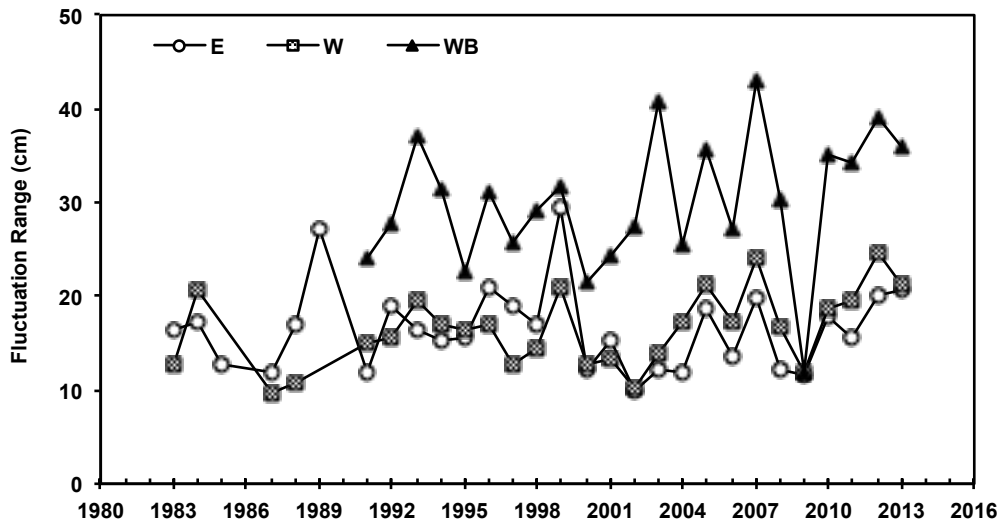


Fig. 2-4 Fluctuation range of GWT at three sites from 1983 to 2013

Table 2-2. Average errors of three sites from 1983 to 2013

Case	Site E (n = 29)			Site W (n = 24)			Site WB (n = 21)		
	CHI (10^{-3})	AE	<i>r</i>	CHI (10^{-3})	AE	<i>r</i>	CHI (10^{-3})	AE	<i>r</i>
1	12.3	2.81	0.85	11.6	2.66	0.89	20.1	5.87	0.85
2	2.6	0.93	0.92	2.0	0.81	0.94	12.3	1.90	0.93
3	2.5	0.91	0.94	1.9	0.77	0.95	11.8	1.88	0.93
4	2.9	0.97	0.92	1.9	0.79	0.95	15.1	2.11	0.92

CHI: chi-square error (cm); AE: absolute error (cm); *r*: correlation coefficient.
n: number of observed years.

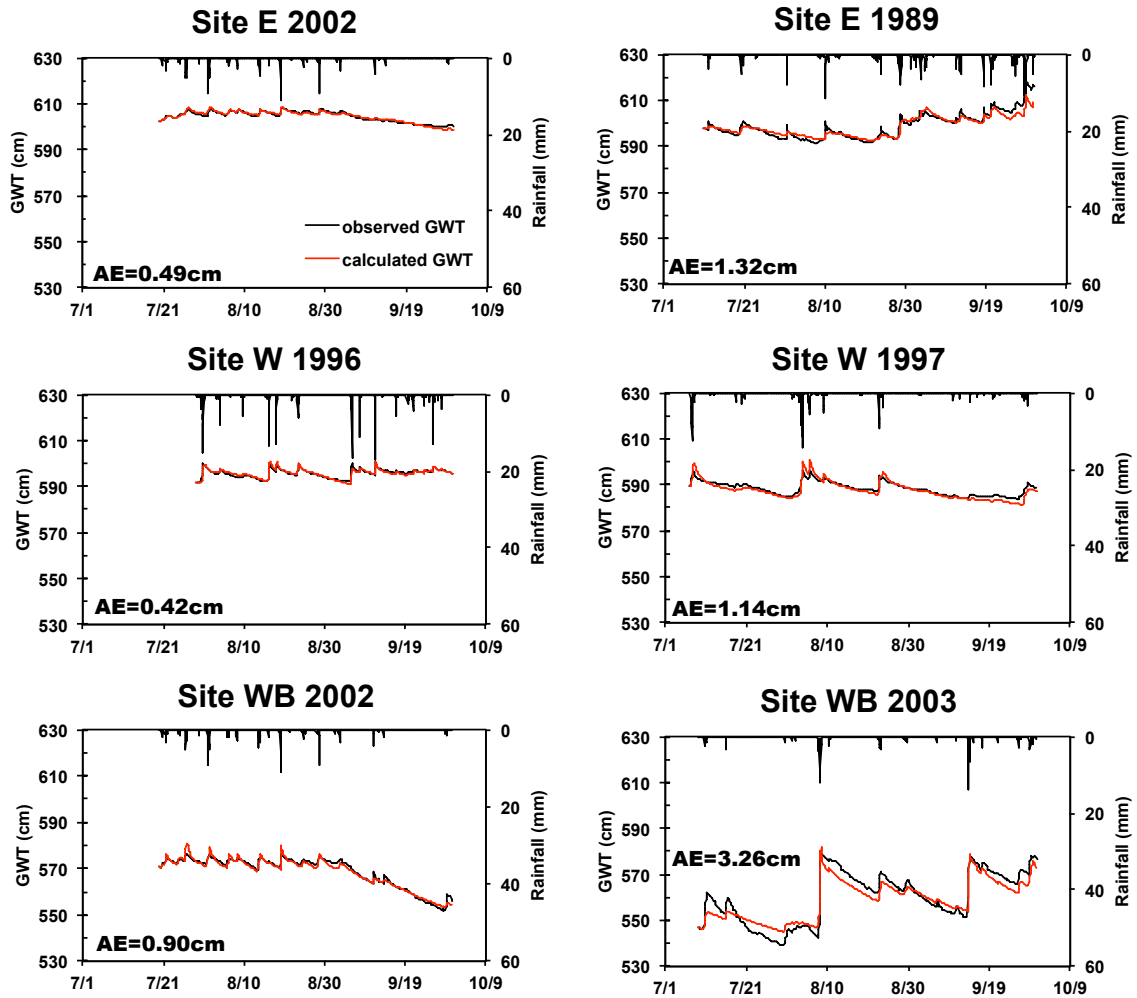


Fig. 2-5 The simulation results for the minimum error (left row) and maximum error (right row) at each site using simulation Case 3 (AE: absolute error)

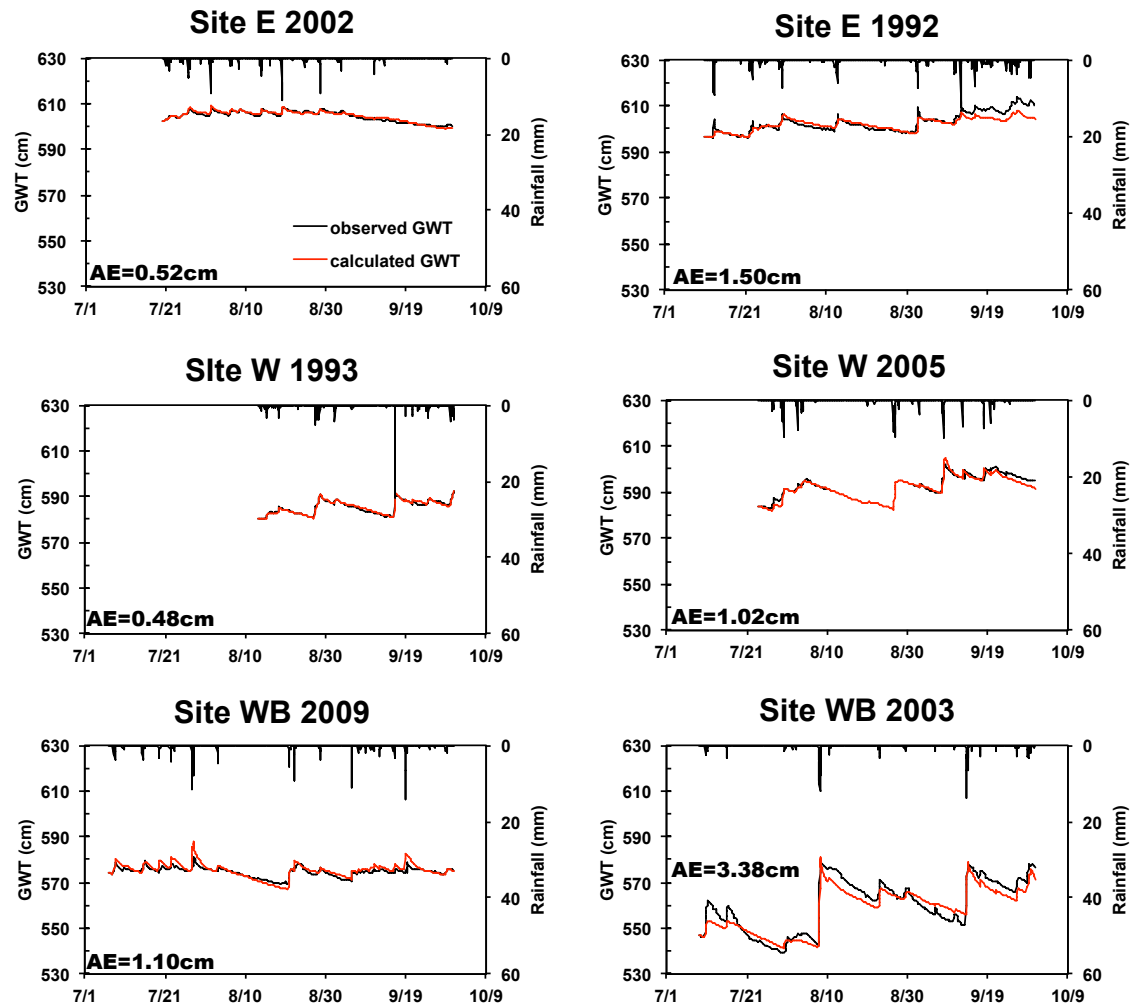


Fig. 2-6 The simulation results for the minimum error (left row) and maximum error (right row) at each site using simulation Case 4 (AE: absolute error)

2.3.4 Comparison of GWT fluctuation patterns by site in a single year

In this section, the simulation results of three sites by two cases in a single year were selected to explain the meaning of each parameter, which reflect the GWT fluctuation patterns. Figure 2-7 shows the simulation results by using simulation Case 3 (Fig. 2-7 a) and Case 4 (Fig. 2-7 b) at sites E, W and WB in 2012. Values for the parameters are shown in Table 2-3 with r , NSE, CHI and AE characterizing the calculation errors.

The parameters for PTM quantitatively represent the difference in GWT fluctuation patterns among different locations. In cases 3 and 4, parameter C at Site E (= 1.5) was smaller than those at sites W (= 1.8) and WB (= 3.1). Because the value for C represents the ratio between GWT increase and the amount of rainfall, a value of 1.5 means that GWT at Site E rose by 15 mm with a rainfall of 10 mm, if the effect of outflow is neglected. The values for C at Site W and Site WB similarly indicate that GWT at those two sites rose by 18 mm and 31 mm, respectively, with the same amount of rainfall as that of Site E.

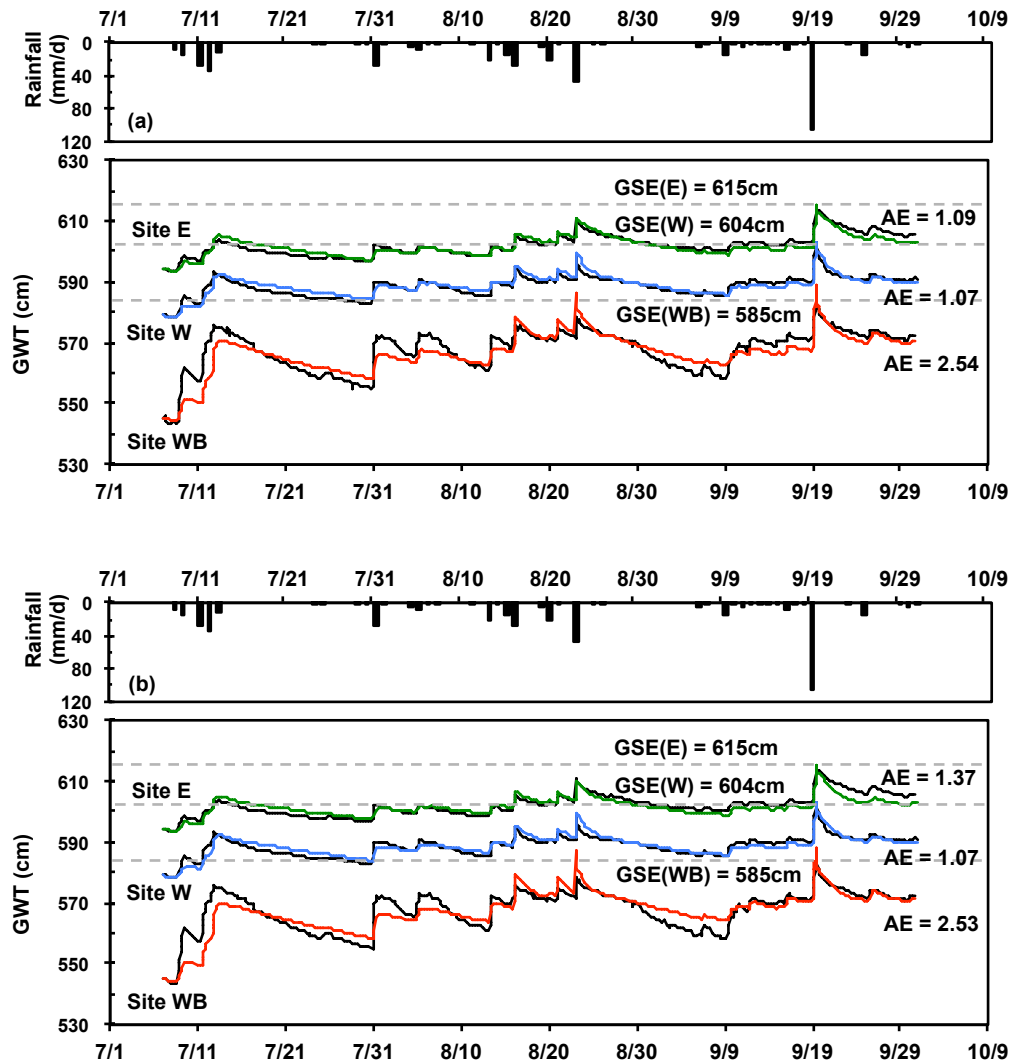


Fig. 2-7 The simulation results for GWT fluctuations at three sites in 2012 in Case 3 (a) and Case 4 (b). Observed and simulated GWT are shown by black line and coloured lines, respectively. Daily rainfall is shown as a vertical bar graph at the top of the figure. Calculation is from 7 July to 30 September. Straight dashed lines indicate average ground surface elevation (GSE) at each site. AE: absolute error (cm)

Table 2-3. Parameter values and errors for simulation Case 3 and Case 4 in 2012

Case	Site	Parameters							CHI (10^{-3})	AE	r
		C	$A1$	$A2$	$A3$	$HA1$	$HA2$	$HA3$			
3	E	1.5	0.0005	0.01	1	562.9	602.9	612.9	2.9	1.09	0.93
	W	1.8	0.0005	0.02	1	550.3	590.3	600.3	2.8	1.07	0.93
	WB	3.1	0.0010	0.02	1	531.6	571.6	581.6	19.7	2.54	0.88
4	E	1.5	0.0002	0.02	1	516.9	602.9	612.9	4.3	1.37	0.90
	W	1.8	0.0002	0.02	1	491.3	590.3	600.3	2.8	1.07	0.93
	WB	3.1	0.0002	0.02	1	415.6	571.6	581.6	22.0	2.53	0.86

HAi : cm; CHI: chi-square error (cm); AE: absolute error (cm); r : correlation coefficient.

In Case 3, the ratio of GWT drawdown for each peat layer could be characterized by the value of $A1$, $A2$ and $A3$. The ratio of GWT drawdown specifically in the lower peat layer (between $HA1$ and $HA2$) is represented by $A1$. In the middle peat layer (between $HA2$ and $HA3$), the ratio is represented by $A1$ and $A2$. The ratio in the upper peat layer (higher than $HA3$) is represented by $A1$, $A2$ and $A3$. In the lower layer, the ratios of GWT drawdown at sites E and W were similar, but the ratio at Site WB was twice that at sites E and W ($A1$ of Case 3). In the middle and upper layers, the ratios of GWT drawdown were different, wherein the largest ratio was at Site WB and the smallest was at Site E.

The parameters of PTM depict the GWT fluctuation feature by layer: at the lower layer during dry period, GWT at Site E decrease slow and similarly with Site W; when GWT rising to the middle and upper layer due to rainfall, GWT at Site W decrease faster than Site E. Throughout the whole peat layer, the GWT at Site WB decrease faster than sites E and W. During the same rain event, the ratio between water table increase and rainfall amount at Site E is the smallest and that at Site WB is the largest (Fig. 2-7).

In Case 3, values of $HA1$ (VDs were fixed as 40 and 10 cm) and GSEs (Fig. 2-7) at the three sites had a descending order Site E > Site W > Site WB.

In Case 4, the ratio of GWT drawdown could be reflected by VD_{21} ($HA2-HA1$) due to the size of each plughole had been fixed (Ai in Case 4, Table 2-3). When the size of each plughole was the same, VD_{21} of Site WB (= 156 cm) is larger than that of Site E (= 86 cm) and Site W (= 99 cm). That is, the plughole size was shrunk 100 times (0.02/0.0002), the vertical distance between the lower two plugholes are varied: VD_{21} at Site WB is almost twice that at Site E.

We highlight that such differences of GWT fluctuation patterns among three sites, which are observed in a single-year pattern comparison, were also found in the other years. As a brief conclusion, wider FR for GWT can be characterized by larger parameter values for C , AI and VD_{21} .

2.3.5 Long-term analysis for GWT fluctuation patterns at three sites

In this section, spatial variability and long-term variations of GWT fluctuation patterns were explicated by the 30 years' simulation results using PTM. The relationship between parameters and affecting factors were investigated. Finally, the difference between Case 3 and Case 4 are discussed.

a. Spatial variability among the three sites

The parameters of simulation results at each site for Case 3 through almost 30 years of GWT simulations are shown in Figures 2-8 and 2-9 and list in Appendix Table 1. The parameters for Case 4 are shown in Figure 2-10 and list in Appendix Table 2. From 1983 to 2013, the averages for C , AI , $A2$, $HA2$ and $HA2-HA1$ were in the order Site E < Site W < Site WB.

C for Case 3 and Case 4: Values for C at Site W (average = 2.3) were almost (except 1999) larger than those at Site E (average = 1.9) ($P < 0.05$) (Fig. 2-8 and Fig. 2-10). Moreover, the C values at Site WB (average = 4.3) were almost twice those at Site E, indicating that with the same amount of rainfall, the magnitude of GWT increase was the greatest at Site WB and smallest at Site E. A larger value for C means less effective porosity for water storage in peat. Therefore, the effective porosity of peat was in the descending order Site E > Site W > Site WB.

Generally, the structure of peat can be distinguished by porosity (n) and bulk density

(BD) ($n = 1 - \text{BD}/\text{PD}$, where PD is particle density) (Whittington and Price 2006). The bulk density of a peat surface is usually small because of porosity. In many cases, within 30 cm depth, bulk density increases in proportion to peat decomposition (Lindsay 2010); therefore, the greater the depth from the surface, the greater the bulk density. Briefly, less decomposed peat has a smaller bulk density (Lindsay 2010). However, such important features of peat are very difficult to directly and accurately measure because it is difficult to collect flabby peat samples without disturbance. C can be used as a relatively effective parameter to express the structure of peat.

$A1$ and $A2$ for Case 3: The difference in $A1$ between sites E and W was not obvious ($P > 0.05$); however, this difference was significant between Site WB and the other two sites ($P < 0.01$). Contrastingly, the difference in $A2$ between Site W and Site WB was small ($P > 0.05$). Values for $A2$ at Site E were significantly smaller than at Site W and Site WB ($P < 0.01$) (Fig. 2-8), suggesting that the basic water loss ($A1$) from the peat layer (mainly from the catotelm) was similar between sites E and W, and the basic water loss at Site WB was larger than that at sites E and W. Water losses from the middle and upper peat layers ($A2$) (part of the acrotelm) at sites W and WB were similar and much greater than that at Site E. In conclusion, during high GWT conditions, Site W had similar basic water loss as Site E and had large water loss from the upper peat layer similar to Site WB. Peat is the incompletely decayed remains of plants that grew on what used to be the surface (Clymo *et al.* 1998). Across several decades, under different vegetation conditions, the composition of peat soil in the upper layer should vary (within a certain range of thickness) between the three sites. Using the results from this paper, the nature of the peat soil can be clarified. Firstly, the peat at Site WB (dominated by the *Sasa* community) had the smallest effective

porosity and strongest response of GWT to rain events and dry events among the three sites. Secondly, the peat at Site W (located on the front line of the *Sasa* community invasion of the *Sphagnum* community) had less effective porosity for water storage and greater water loss of peat soil than that at Site E (dominated by the *Sphagnum* community). Here, 'peat' suggests the peat layer from the ground surface to the maximum groundwater depth (minimum height of GWT).

HA2 for Case 3: Figure 2-9 shows the values for HA2 in Case 3, i.e. each year's upper tertile for GWT at the three sites, wherein HA2 and average GSE were in the descending order Site E > Site W > Site WB. The difference in the average HA2 between sites E and W (11.7 cm) and the difference in the average GSE (11.0 cm) were similar, suggesting that the difference in HA2 at sites E and W reflects the site elevation difference. Contrastingly, the difference in the average HA2 between sites W and WB (20.7 cm) was larger than the difference in the average GSE (14.0 cm), indicating that HA2 at Site WB was lower than that at the other two sites. This is caused by the lower GSE at Site WB and the effects of the wider GWT fluctuations at Site WB.

HA2 value represents the GWT position during a certain period. The very low elevations of outlet plugholes at Site WB indicate the GWT fluctuations there were wider and occurred within a deeper peat layer relative to the other two sites during the dry period (from July to September). Thus, the wet and dry conditions of peat soil at Site WB changed dramatically. The wider and dramatic GWT fluctuation may change the wet and dry conditions of peat soil at Site WB, which facilitates the growth of *Sasa*. Compared with the narrow and smooth GWT fluctuations of the *Sphagnum*

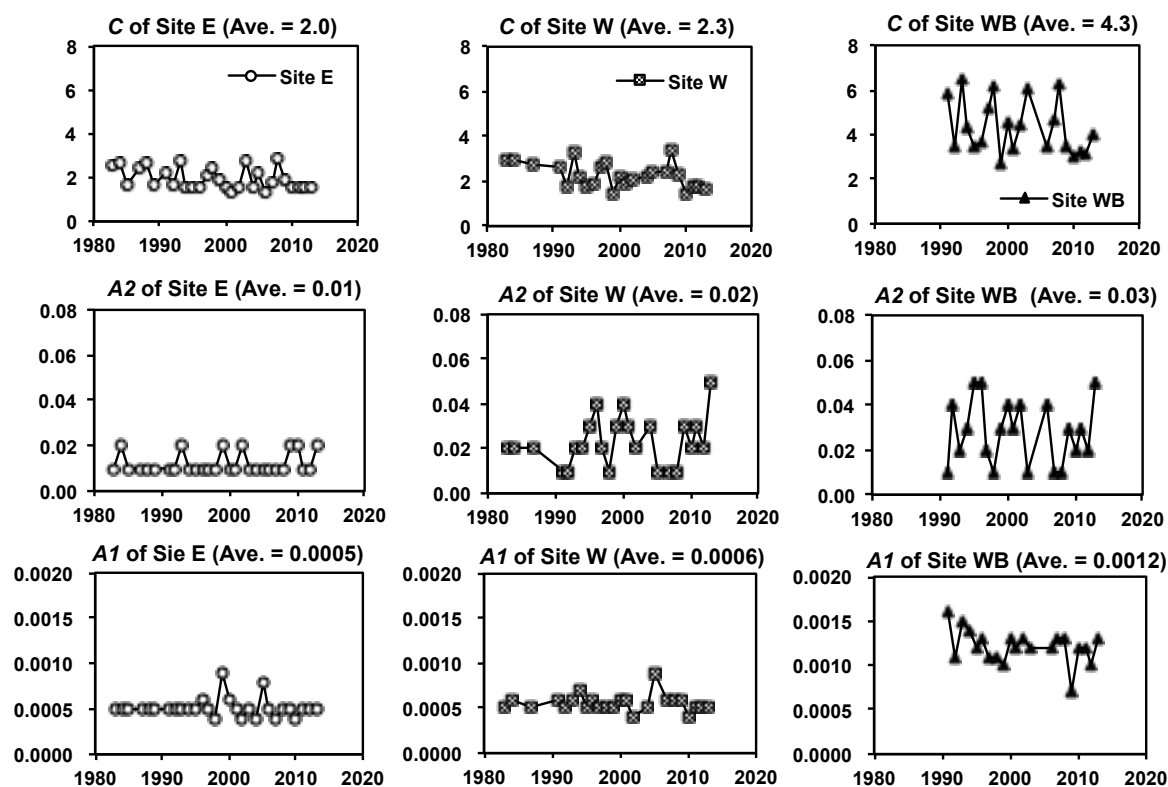


Fig. 2-8 The long-term trends for the PTM parameters in Case 3

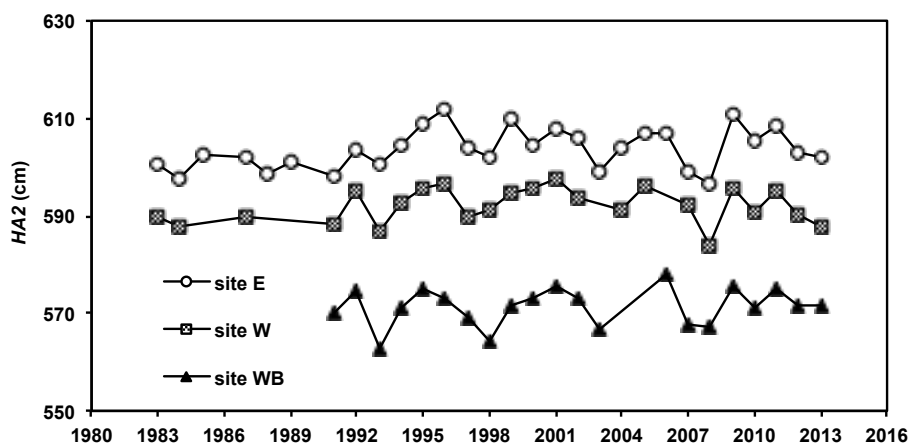


Fig. 2-9 The long-term trends of *HA2* (upper tertile) in Case 3

Average values of *HA2* at Sites E, W and WB are 603.7 cm, 592.0 cm, and 571.3 cm, respectively

community, the *Sasa*-invaded site had drastic GWT fluctuations, which may accelerate the decomposition of peat (Hilbert *et al.* 2000; Belyea and Clymo 2001).

HA2–HA1 for Case 4: Figure 2-10 shows vertical distance between the lower two outlet plugholes *HA2–HA1* (VD_{21}). Under the same conditions for the three plugholes in Case 4 ($A1 = 0.0002$, $A2 = 0.02$ and $A3 = 1$), there were significant differences in VD_{21} among the three sites. The average VD_{21} at Site WB was nearly twice that at Site E and Site W, suggesting that the unit-time GWT drawdown from the lowest plughole *QA1* (cf. Equation 2-2) at Site WB was larger than that at Site E and Site W. The larger VD_{21} (i.e. deeper *HA1*) indicates more rapid water loss and weaker water holding abilities of the peat. Average values of *HA2–HA1* during the last 29 years at sites E, W, and WB were 95 cm, 104 cm, and 207 cm, respectively.

b. Long-term variations at the three sites

In Case 3, the changes in parameter *C*, *A1* and *A2* over the last 30 years at the three sites revealed no clear trends (Fig. 2-8). However, all parameters at Site WB varied more extensively compared with Site E, and *A2* at Site W showed wider variation than that at Site E. A slight uptrend was observed in *HA2* at Site E (slope = 0.15 cm/y; $P > 0.05$) and at Site W (slope = 0.05 cm/y; $P > 0.05$; Fig. 2-8), indicating that the peat at Site E accumulated at a speed of 1.5 mm/y over the period 1983–2013. This fits the universal standard for the accumulation rate of peat. From 1991 to 2013, an uptrend in *HA2* (slope = 0.09 cm/y; $P > 0.05$) has been also shown at Site WB.

In Case 2, VD_{21} at Site WB decreased (slope = -1.4 cm/y; $P > 0.05$) over the last 30 years (Fig. 2-10). In comparison, VD_{21} at sites E and W remained nearly unchanged ($P > 0.05$).

In both cases, all parameters at Site WB showed high variability over the 30 years.

The peat at sites E and W remained in a relatively steady state. However, the changes in all parameters at the three sites in all cases were not statistically significant.

2.3.6 Difference between Case 3 and Case 4

The difference between Case 3 and Case 4 is: number of the parameters in Case 4 (C and $HA2-HA1$) is less than Case 3 (C , AI , and $A2$); the simulation errors of Case 4 is larger than that of Case 3.

In Case 3, GWT fluctuations can be characterized by variations of parameters C , AI , and $A2$. In Case 4, the fluctuations are represented by C and $(HA2-HA1)$. In practice, the number of parameters is smaller in Case 4 than in Case 3. This simplifies the verification but enlarges the error.

When the GWT are absolute water tables with respect to certain benchmarks (such as sea level or the ground surface), change of $HA2$ can indicate the accumulation speed of peat. But if the GWT data do not have a height reference from a benchmark, $HA2$ has no common meaning or information in relation to the ground surface or elevation above sea level. Regardless of whether the GWT were absolute water table, GWT fluctuations could be characterized by variations of parameters C , AI , $A2$ or $HA2-HA1$.

In practice, GWT calculated with respect to certain reference levels are meaningful in the simulation of long-term variations: the trend of long-term change in $HA2$ can characterize long-term variations of peat thickness.

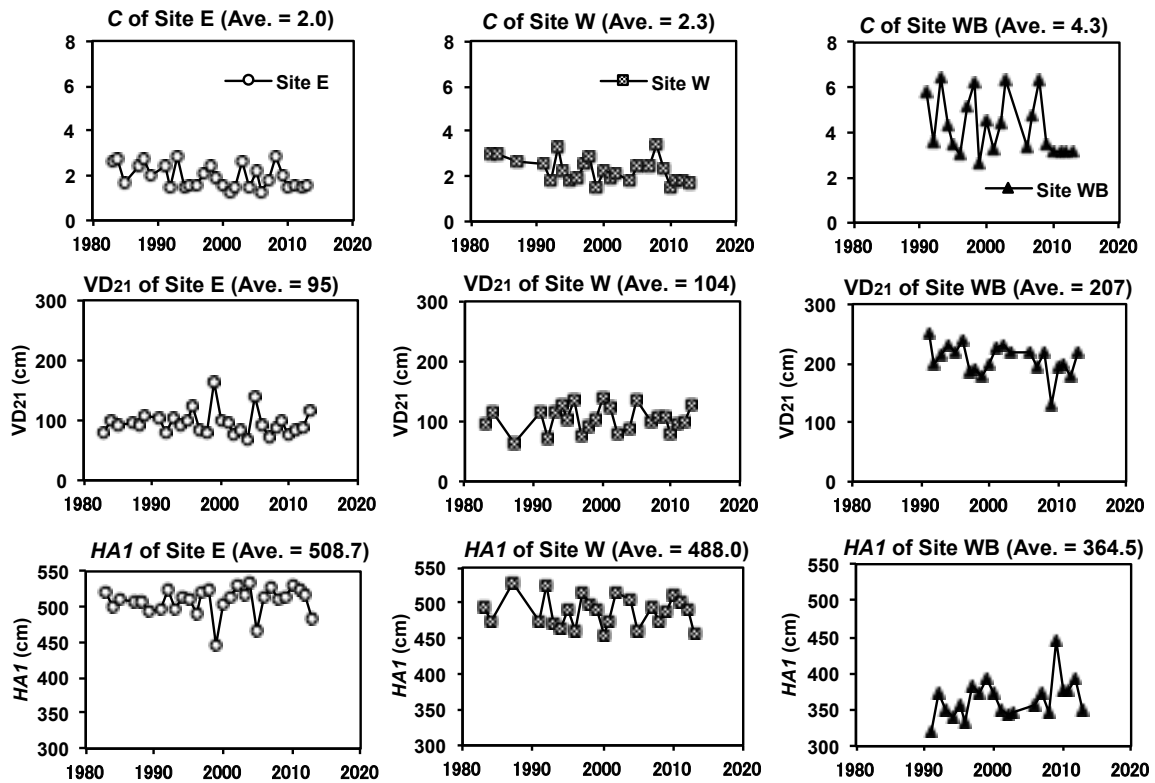


Fig. 2-10 The long-term trends for the PTM parameters in Case 4
VD₂₁: vertical distance between the lower two plugholes (*HA2*–*HA1*)

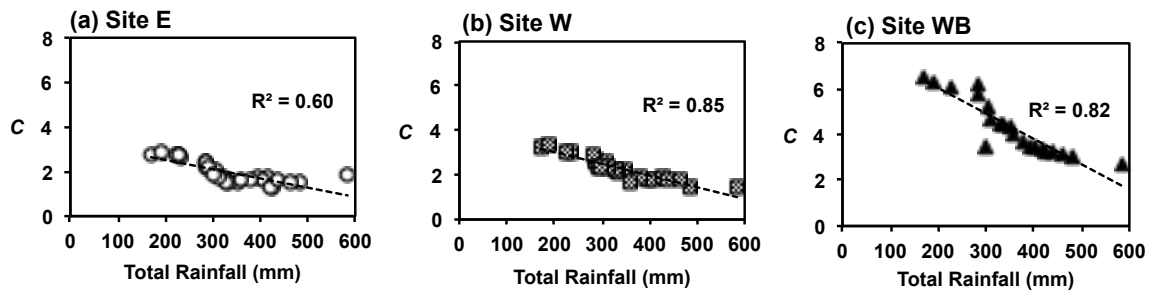


Fig. 2-11 Relationship between *C* and total rainfall from July to September

2.3.7 Factors affecting PTM parameters

Results from the multiple regression analysis indicate a strong regression association relationship between C and total rainfall amount during the observed period at each site (Fig. 2-11). The coefficient of determination (R^2) exceeded 0.80 ($P < 0.01$) except at site E ($R^2 = 0.60$) ($P < 0.01$). This association relationship can be partially explained by the study of Suzumura *et al.* (2007), which showed that effective porosity increases in peat nearer the peat surface. The GWT rises when the amount of rainfall increases and its moisture reaches upper peat layers, and the effective porosity of peat increases, thereby reducing the ratio of water table increase. However, the regression association relationships between C and other characteristic values were unclear (e.g. total duration of rain events, rainfall intensity, longest rain-free days, average GWT and minimum and maximum GWT). $A1$, $A2$, $HA2$ and $HA2-HA1$ also revealed no strong association relationships with the characteristic values for rain events and GWT at the three sites ($R^2 < 0.50$).

2.4 Conclusions

This chapter reveals an evaluation method for GWT fluctuations of bog by using PTM. The fluctuation patterns of GWT can be numerically expressed by PTM parameters. It can achieve the simulated GWT of accuracy of less than a few centimetres. Four rules and two simulation cases were established and the number of parameters was reduced from seven to three or two. The effectiveness of this model was validated by the simulations, which used 29 years of GWT data from Genseikaen, Sarobetsu Mire, Hokkaido, Japan.

At Genseikaen of Sarobetsu Mire, three sites were observed and have different vegetation cover. But the GWT fluctuations of two observation sites (E and W) were similar, and it was difficult to distinguish the subtle difference visually.

Using the PTM, the various characteristics of GWT rise could be represented by parameter C (a large C value indicates a large ratio of GWT increase). The difference of GWT drop could be described by parameter Ai (a large $A1$ value indicates greater basic and constant water loss from the peat layer, and a large $A2$ value indicates rapid water loss in the upper peat layer). Thus, large values of parameters C and Ai indicate that the GWT response to rain and dry events had wide variation and large ratios of GWT rise and drop. Moreover, these parameters could also represent properties of peat soil. A larger C value indicates smaller effective porosity and water storage of peat. A larger Ai value means that the GWT decreases rapidly so the peat becomes drier during rain-free periods. Long-term variations of the parameters reflect peatland stability. There was drastic variation in the parameters at observation site (WB) dominated by a *Sasa* community from 1991 to 2013, whereas long-term parameter changes were slight at the other two sites (E and W) from 1983 to 2013. Site WB had unstable GWT conditions relative to those at E and W, which mean that the latter two sites were tolerant of annual climate conditions, whereas WB was susceptible to those conditions.

The PTM offers a simple means for evaluating the hydrologic environment using only monitoring data of GWT and rainfall. The model can be implemented without much computational complexity. In the present study, three rules and four simulation cases were established for computational simplicity and greater accuracy. In Case 2, errors were minimized but the numbers of parameters were greater than in Cases 3 and 4. However, PTM simulation was simplified in Case 4 but the error increased. If high

computational accuracy is not required, Case 4 is appropriate. For different types and situations of peatland, the simulation method can be varied.

The seasonal response of ET and amount of soil moisture in unsaturated peat surface soils were not considered here. The applicability of the proposed method should be further extended to cases of fens, GWT without benchmarks, or peatland in different regions or climates.

CHAPTER 3

Evaluation of shallow groundwater table data without height reference from benchmark

3.1 Introduction

Long-term monitoring of shallow groundwater table (GWT) is essential for the investigation and evaluation of the hydrologic environment. In most hydrological investigations of peatland, the GWT data are monitored and recorded in the form of groundwater depth, even of groundwater level that is not measured with respect to specific reference benchmarks such as sea level or ground surface. Especially, the GWT data without any reference benchmark have no common meaning or information in relation to the ground surface or elevation above sea level. Thus, they cannot be used effectively for evaluating the hydrological environment in the previous studies.

In view of this situation, this chapter proposes a simple evaluation method based on Peatland Tank Model. By using such GWT data, the model provides satisfactory simulation accuracy and flexibility.

The objective of this chapter is to show how the PTM detects the spatial variability and temporal changes of GWT fluctuation patterns even if the GWT data are not measured with respect to certain benchmarks. The usefulness and effectiveness of the PTM for the shallow peatland GWT are discussed. The meaning and function of each parameter used in the PTM and the PTM usage guideline are also explained.

3.2 Methods

The simulation for the shallow GWT fluctuation is based on the PTM introduced in chapter 2. The algorithm is the same as the equation 2-1 and 2-2, but the time unit (data sampling interval) for estimating GWT is 2 hours.

Two simulation cases were implemented and several rules were established (Table 3-1). Based on these rules, the number of parameters in the PTM was reduced from the original seven to three (Case 1) or two (Case 2). We adopted PTM with 29 years of GWT data recorded (1983–2012, except for 1998) at Ochiai, Sarobetsu Mire, northern Hokkaido (approximately 45°8'N, 141°44'E). GWT was observed at three sites: Site D near a drainage ditch along the peat mining location; Site M at the edge of the peat mining area; and Site U in an unused area far from the drainage (Fig. 3-1). Annual average temperature in this area is approximately 6.1 °C, varying from –6.5 °C in February to 19.6 °C in August. Annual average precipitation is 1,073 mm (Japan Meteorological Agency). On average, the warm period without snow cover lasts from mid-April through late October. All calculations were performed for July through September. The observed GWT data were not measured with respect to certain benchmarks, so their values had no common meaning or information in relation to the ground surface or elevation above sea level.

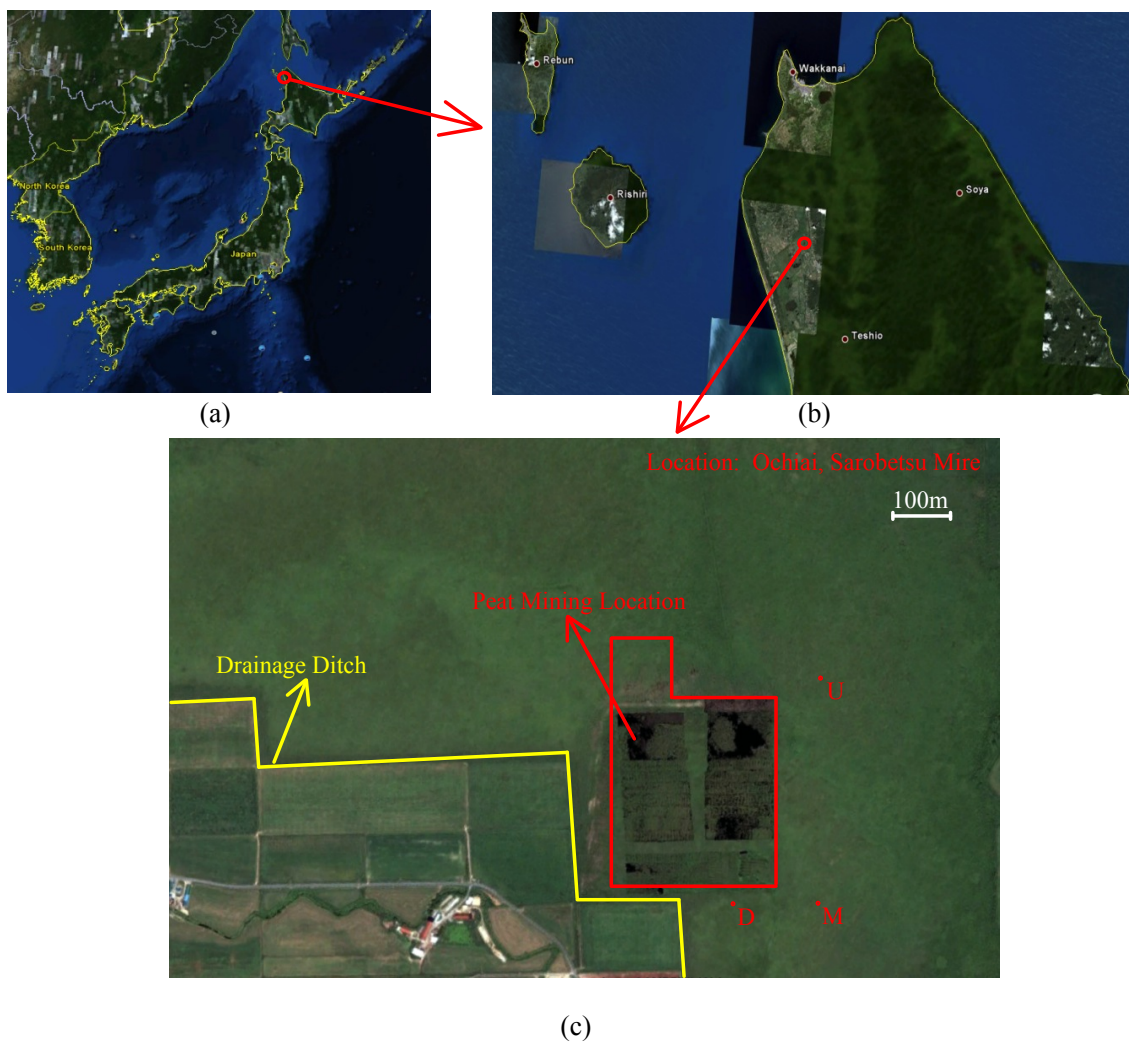


Fig. 3-1 Observation sites in Ochiai, Sarobetsu Mire, northern Hokkaido
 (a): Hokkaido in Japan; (b) Ochiai, Sarobetsu Mire;
 (c): observation sites (red points): D, M and U; Peat mining location
 (surrounded by red lines); Drainage ditch (yellow line).

Table 3-1 Simulation cases in Ochiai, Sarobetsu Mire

Case	Manipulated Parameters	Fixed or Automatically Determined Parameters	Rules
1	$C, A1, A2$	$A3, HA1, HA2, HA3$	*1, *2
2	$C, HA1$	$A1, A2, A3, HA2, HA3$	*2, *3

*1: $HA1 = HA2 - 40$ cm, $HA3 = HA2 + 10$ cm or $HA3 = \text{GWTm}$ (if $(HA2 + 10 \text{ cm}) > \text{GWTm}$).

*2: $HA2$ is equal to the value of upper tertile of GWT data calculated via the following steps. In the first step, all observed GWT data within the calculation period at each site were sorted numerically, in descending order. This set should include every datum, even if there are overlaps. Then, the value found one third of the way down from the maximum in the organized dataset is defined as the upper tertile.

*3: $A1 = 0.0003$, $A2 = 0.03$, $HA3 = HA2 + 10$ cm or $HA3 = \text{GWTm}$ (if $(HA2 + 10 \text{ cm}) > \text{GWTm}$). GWTm: the maximum GWT.

In all cases, $A3 = 1$

In PTM computations, the parameters were adjusted repeatedly until the optimum simulation result was attained, where the chi-square error (CHI) and absolute error (AE) were minimized and the correlation coefficient (r) was maximized. Values of each parameter were compared by site and examined by one-way analysis of variance (ANOVA). ANOVA significance levels were set to 0.05. Based on 29 years' GWT observations at each site, long-term trends of each parameter were evaluated by the coefficient of determination (R^2). All statistical tests were conducted using SPSS 16.0 statistical software (SPSS Inc., Chicago, IL, USA).

3.3 Results and discussion

3.3.1 Comparison of the GWT fluctuation patterns

Throughout the results from 1983 to 2012, parameter C was in the order of Site D > Site M > Site U, from both methods (Fig. 3-2). This indicates that the magnitude of GWT rise in response to rain events was maximum at Site D and minimum at Site U. A larger value of C means less effective porosity for water storage in peat (Umeda and Inoue 1985). Therefore, it is concluded that the effective porosity of peat at the three sites was in the order Site D < Site M < Site U. At the three sites, changes of parameter C over the last 29 years do not show clear trends ($P > 0.05$) (Fig. 3-2). However, there is a strong negative regression relationship between C and total amount of rainfall from July through September at all sites (Fig. 3-3). From Case 1, R^2 at Site D exceeded 0.80 ($P < 0.01$). This relationship can be explained by the fact that effective porosity increases in peat nearer the ground surface. When the amount of rainfall increases, the GWT may spend more time in the upper part of peat layer, where the effective porosity of peat is relatively large and the ratio of GWT rise (C)

becomes small.

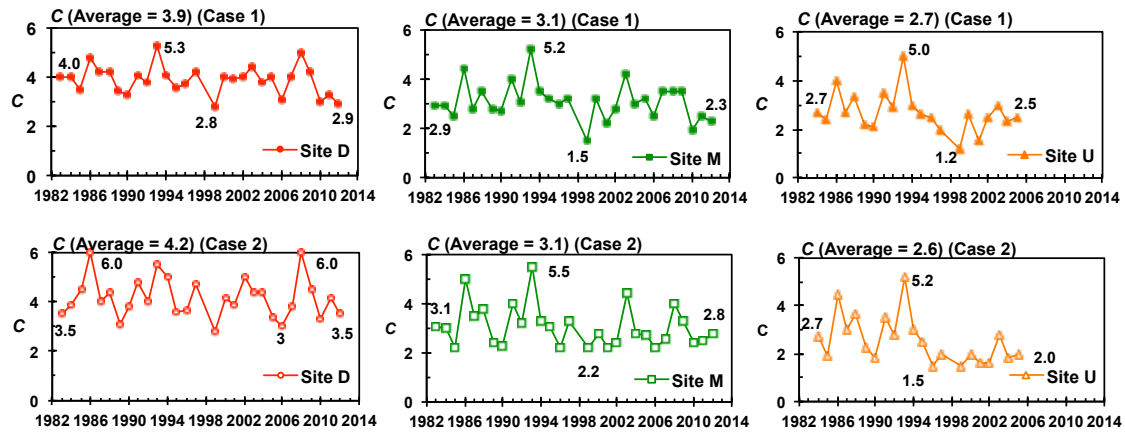


Fig. 3-2 Variation of parameter C at three sites from 1983 to 2012

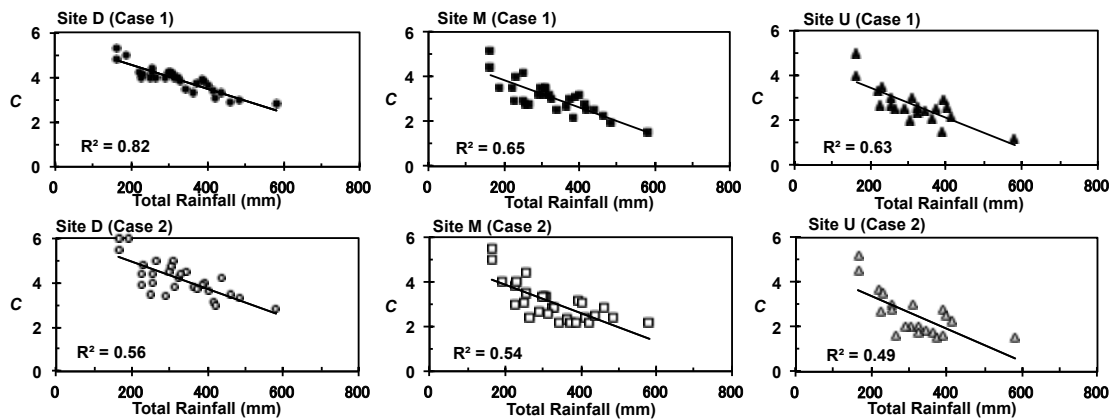


Fig. 3-3 Relationship between parameter C and total rainfall (July through September) at three sites from 1983 to 2012

In Case 1, GWT fluctuations can be characterized by variations of parameters C , $A1$, and $A2$. The difference of $A1$ between Sites M and U was not obvious ($n=21$, $P > 0.05$); however, this difference was significant between Site D and the other two sites ($n=28$ for Site D and M, $n=21$ for Sites D and U, $P < 0.01$) (Fig. 3-4). Differences of $A2$ among the three sites were not obvious ($P > 0.05$). The average $A2$ at site U ($n=21$, average = 0.03) is smaller than those at the other two sites ($n=28$ for Site D, $n=29$ for Site M, average of both sites = 0.04). Parameters $A1$ and $A2$ at all sites over the last 29 years do not show clear trends ($P > 0.05$). The fact that the value of $A1$ at Site M was similar to that at Site U means that characteristics of basic and constant water losses from the peat layer (mainly from the catotelm) were similar at those two sites. In contrast, a larger $A1$ at Site D means that the amount of water loss was greater than at the other two sites. Similarly, $A2$ at the three sites was nearly identical, which indicates that water losses from the upper peat layer (part of the acrotelm) at the three sites were similar. In conclusion, Site D had greater water loss compared with the other two sites, but water loss of the upper peat layer at all three sites were similar.

In Case 2, GWT fluctuations are represented by parameter C and $(HA2-HA1)$. Figure 3-5 shows variations of vertical distances among the outlet plugholes $(HA2-HA1)$ and $(HA3-HA2)$ at the three sites. Under the same condition of $A1 = 0.0003$, $A2 = 0.03$, and $A3 = 1$ for the three plugholes, there were significant differences in $(HA2-HA1)$ among the three sites. Average values of $(HA2-HA1)$ during the last 29 years at sites D, M, and U were 30.3 cm, 22.7 cm, and 17.8 cm respectively. The greater vertical distance (i.e. depth of bottom plughole) at Site D means that the unit-time GWT drawdown from the bottom plughole $QA1$ (cf. Equation

2-2) at Site D was larger than those at sites M or U. Thus, the larger value of $(HA2-HA1)$ indicates more rapid discharge. Over the same period, $(HA2-HA1)$ at site D increased, with slope 0.27 cm/year ($P < 0.05$). $(HA2-HA1)$ at Site M increased by 0.12 cm/year and decreased by -0.21 cm/year at Site U, but the trend was not significant for either ($P > 0.05$) (Fig. 3-5). The $(HA3-HA2)$ at Site D is larger than sites M from 1989, but during 1983 to 1988 $(HA3-HA2)$ at Site D is similar to sites M. The $(HA3-HA2)$ at Site U is smaller than other two sites over 29 years.

The reason for such a change may be inferred as follows. In summer 1983, the drainage ditch near these three sites was dredged and deepened. In the following few years (1983–1989), leakage of water by piping from the adjacent mining pool to the ditch was observed. In terms of parameter variation, $(HA2-HA1)$ increased yearly in this period. In the last 29 years, drainage intensity at Site D clearly increased. However, at sites M and U, variations of drainage intensity were not as significant. This fact indicates that drainage changed the water loss characteristics of peat and its influence persisted in the following years.

The three observation sites have different drainage conditions. However, it is difficult to distinguish the difference of GWT fluctuations visually, so these fluctuations appeared similar. Using the PTM, various characteristics of GWT rise could be represented by parameter C , and GWT drop could be described by parameters A_i and $(HA2-HA1)$. Large values of parameters C , A_i and $(HA2-HA1)$ indicate that GWT may response to rain and dry events greatly. Moreover, differences of A_i among observed sites were able to reflect site differences of drainage characteristics in various peat layers (Case 1). Variations of $(HA2-HA1)$ could depict long-term trends of drainage characteristics at each site (Case 2). In addition, the parameters could also

represent peat properties. A larger C value indicates less effective porosity and less water storage of peat. Larger A_i and $(HA2-HA1)$ values indicate that the GWT decreases rapidly so that the peat becomes drier during rain-free periods.

There is a strong regression relationship between parameter C and total amount of rainfall. Therefore, this amount during the simulation period gives hint to the determination of C . For instance, the value of C in a year with greater rainfall would be smaller. In the case of greatly changed drainage conditions, simulation by Method 1 was unable to match actual GWT fluctuations, because the distance between $HA1$ and $HA2$ was fixed at 40cm. For instance, if a drainage channel was renewed or newly excavated near the observation site, drainage may have intensified and the drop of GWT from the height of $HA2$ may have exceeded 40cm. Under such circumstances, Case 2 is considered more suitable than Case 1. In practical use of the PTM, the vertical distance and size of each plughole could be adjusted according to peatland conditions at individual sites. Additionally, the principle of computation, such as simulation rules and methods, could be adjusted to meet specific peatland conditions.

Average simulation errors of all calculations are shown in Table 3-2. By applying the rules in the footnote of Table 3-1, Case 2 could simplify the computation by decreasing the number of parameters to be fit, but simulation error might become slightly larger than that of Case 1. Moreover, through Case 2, site differences were shown more clearly by the obvious differences of $(HA2-HA1)$ at the three sites, and the trend of long-term drainage effects also became apparent through yearly decline of the depth of the bottom plughole at Site D.

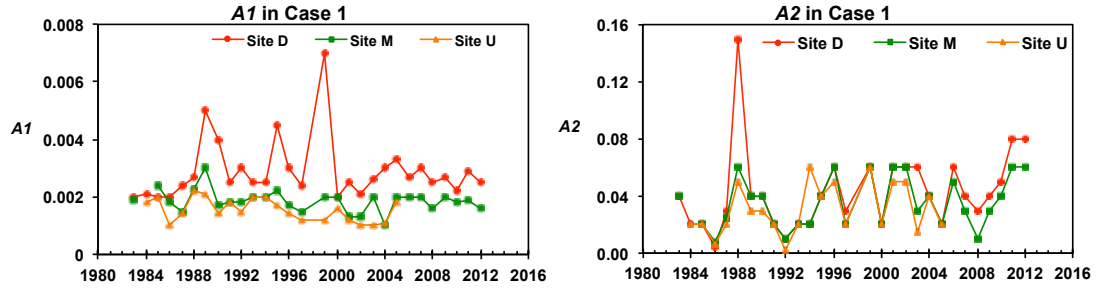


Fig. 3-4 Trends of $A1$ and $A2$ over 1983–2012 at three sites, in Case 1

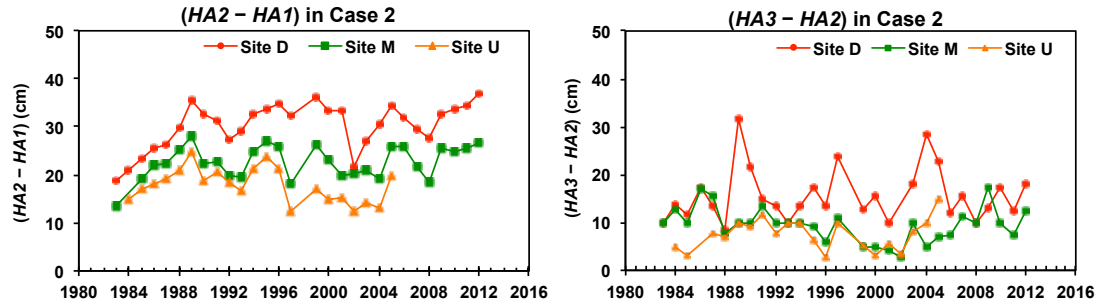


Fig. 3-5 Trends of $(HA2-HA1)$ and $(HA3-HA2)$ over 1983–2012 at three sites, in Case 2

Table 3-2 Average errors of three sites for two cases

Case	Site D (n=28)			Site M (n=29)			Site U (n=21)		
	CHI (10^{-3})	AE	r	CHI (10^{-3})	AE	r	CHI (10^{-3})	AE	r
1	13.7	1.82	0.93	7.1	1.40	0.93	5.7	1.23	0.94
2	13.4	2.05	0.92	7.6	1.48	0.91	8.1	1.40	0.91

CHI: chi-square value (cm); AE: absolute error (cm); r : correlation coefficient.

n: number of observed years

3.3.2 PTM usage guidelines

As abovementioned in chapter 2 and 3, the regression association relationship between parameter C and total rainfall amount was strong. Thus, the amount of total rainfall during calculation period can help to determine C .

When the GWT data are the absolute GWT (above sea level), the long-term change in $HA2$ for Case 1 can represent the long-term variations in peat accumulation or subsidence. However, if the GWT data are not measured with specific reference benchmark, the trend in $HA2$ is meaningless.

In some cases, GWT fluctuations may be greatly altered, e.g. when drainage intensity becomes high (when a drainage channel is newly excavated near the observation site) or low (when a drainage channel is blocked or obstructed). The simulation using Case 1 of chapter 3 (or Case 3 of chapter 2) has the possibility that it cannot represent such a drastic change in GWT fluctuation pattern because of the fixed value of $HA2-HA1$. In such cases, the calculation using Case 2 of chapter 3 (or Case 4 of chapter 2) is considered to be more preferable and $HA2-HA1$ could represent long-term changes in water holding characteristics.

Here, the $HA2$ value was made equal to the upper tertile empirically in cases 1 and 2 of chapter 3, and in cases 3 and 4 of chapter 2; the vertical distances among three plugholes in Case 1 (or Case 3 in chapter 2) and the ratios $A3/A2$ and $A2/A1$ in Case 2 (or Case 4 in chapter 2) were fixed. In other cases of peatland studies, $HA2$ could be set to other values (average or median, etc.) but should be varied within the range of GWT fluctuations; the vertical distances and those ratios could be changed according to the peatland type. The structure of this PTM (number of plughole and tank) could be altered to suit the condition of each peatland, which could expand its application.

3.4 Conclusion

This chapter demonstrated the applicability of the PTM-based evaluation method on the type of GWT data without specific references benchmark. At Ochiai of Sarobetsu Mire, the GWT fluctuations were simulated with accuracy of a few centimeters. The long-term changes in hydrological condition can be distinguished by model parameters at different locations.

The observed GWT data used herein were not measured with respect to specific elevation references or benchmarks (i.e., sea level or ground surface). Using such data, existing methods cannot reveal either the changes in GWT fluctuation patterns or site differences of GWT conditions. Through use of the PTM, such observed GWT data were effectively used for evaluating such changes and differences. A few sets of parameters were obtained on the basis of simulation results. Smaller simulation errors were attained using the PTM. Especially via Case 2, variations and trends of parameters revealed the site differences and long-term changes of GWT condition. The 29-year GWT fluctuations at Site D were the greatest and could be characterized by the largest parameter values. Parameter trends at three sites varied, and were able to reflect the various drainage conditions. Thus, the PTM is a promising method for the evaluation of long-term variations and site differences of hydrologic conditions in peatland.

CHAPTER 4

Modified Peatland Tank Model incorporating evapotranspiration variation

4.1 Introduction

The PTM based evaluation method proposed in the previous chapters possesses the merits of simplicity and less data requirement. However, the effects of evapotranspiration (ET) variations are not considered in this method. This results in estimation with slightly larger error. In this chapter, further improvement was made on the proposed method to incorporate the effects of evapotranspiration variations into the algorithm. Evapotranspiration is an important component of the hydrological cycle and is essential for quantifying water budget. It is difficult to accurately measure ET and the indirect procedures through correlations with meteorological factors have been used for its estimations (Hamon 1961). In many studies (Monteith 1973; Lindström *et al.* 1997; Allen *et al.* 1998; Pearson *et al.* 2002; Ntegeka *et al.* 2014), the potential evapotranspiration has been calculated by Penman method (Penman 1948). The reason for using Penman method is that ET can be calculated by a formula using a series of meteorological parameters collected from meteorological station.

4.2 Methods

For numerical computation of the evapotranspiration of Sarobetsu Mire, Penman method was used. The basic theory of evapotranspiration computation is given in Equation 4-1 (Miura and Okuno 1993):

$$ET_{pen} = \frac{\Delta}{\Delta + \gamma} \times \frac{S}{l} + \frac{\gamma}{\gamma + \Delta} \times f(u_2) \times (e_s - e) \quad (4-1)$$

where ET_{pen} : potential evapotranspiration in mm day⁻¹

Δ : slope of the saturated vapor pressure curve in mbar °C⁻¹

γ : psychrometric constant in mbar °C⁻¹

S : net radiation flux in MJ m⁻² day⁻¹

l : evaporation latent heat of water in MJ 10³m⁻³

$f(u_2)$: a wind function in mm d⁻¹ kPa⁻¹

e_s : saturated vapor pressure in kPa at mean air temperature

e : mean ambient vapor pressure in kPa at the reference height above ground

Actually, the value computed by using Equation 4-1 is the potential evapotranspiration and represents the daily evapotranspiration. To incorporate this method into our algorithm, the computations have to be carried out hourly. The meteorological data required in the computations by using Equation 4-1, such as temperature, wind speed and sunshine duration, etc., are gathered from AMeDAS at Toyotomi, Hokkaido, Japan. It is noted that the relative humidity is also required by equation 4-1. However, it is not readily available at the afore-mentioned location, so we used the data from Wakkanai) which is about 35 km south of Genseikaen, Sarobetsu Mire.

Theoretically, the daytime evapotranspiration is much larger than the night

evapotranspiration. This is mainly caused by the differences of radiation, air temperature, humidity and wind speed between the two periods. In our algorithm, the evapotranspiration at night (from 7:00 pm to 5:00 am) is assumed to be zero. In fact, an average evapotranspiration is used for the daytime computations. The hourly evapotranspiration at daytime (from 6:00 am to 6:00 pm) is equal to the quotient of the total evapotranspiration in one day and the total number of hours during the daytime (12 hours). When the rainfall during time n to $n-1$ is observed, the corresponding evapotranspiration during time n to $n-1$ is considered to be zero.

Based on the discussions above, the estimation accuracy of the proposed algorithm will be increased by considering the evapotranspiration variations. To validate this argument, simulations are carried out to estimate the GWT fluctuations by using the proposed algorithm. The results are presented and analysed in this chapter.

4.2.1 Modification of the presented algorithm in the original PTM

As discussed above, the evapotranspiration variations are computed and used in the proposed algorithm for better accuracy. It indicates a simple modification of the previously presented algorithm as shown in Equation 2-1. Apparently, the evapotranspiration is modified from a constant to a variable. In the original PTM, the evapotranspiration is considered as part of the water loss from the lowest plughole, i.e., evapotranspiration and the basic water loss of peat are both expressed by parameter AI . However, in the modified PTM, AI only represents the basic water loss from the lowest plughole. The evapotranspiration is expressed by using an independent variable:

$$ETr \times ET_{pen}.$$

The algorithm of the modified PTM is shown below:

$$GWT_n = GWT_{n-1} + C \times R_n - \left(\sum_{i=1}^3 QAi_{n-1} \right) - C \times ETr \times ET_{pen(n-1)} \quad (4-2)$$

Here, $ET_{pen(n-1)}$ is the potential evapotranspiration at time $n-1$. ETr is the ratio of evapotranspiration and used to represent the effect of different vegetation cover on the actual evapotranspiration of the peat. In addition, due to every year's meteorological condition is different, we presume ETr at each site can be changed year by year. C is the coefficient of GWT decrease owing to evapotranspiration. The other parameters are the same as in Equation 2-1, which has been explained in the method of chapter 2.

In fact, C is introduced to quantitatively express the capability of water storage of certain type of peat soil. Its reciprocal is known as the effective porosity of peat. A larger C value represents greater GWT variation in response to the external inflow (rainfall) and outflow (ET). For instance, if the amount of rainfall is R_n , the GWT will be increased by $C \times R_n$. Similarly, if the evapotranspiration is $ETr \times ET_{pen(n-1)}$, the GWT will be decreased by $C \times ETr \times ET_{pen(n-1)}$.

4.2.2 Guideline for appropriate parameter selection at Genseikaen, Sarobetsu Mire

To obtain good approximations to the actual GWT fluctuations, appropriate parameters should be selected for the simulations. At Genseikaen, Sarobetsu Mire, the simulation principle of the modified PTM is shown in Table 4-1.

In the improved PTM model, selection rules of *HA2*, the vertical distances among three plugholes and the calculation period are the same as simulation case 3 presented

in chapter 2. Such a decision is made based on the empirical analysis of the previous computations results. In different vegetation surface, the actual evapotranspiration shows disparity. In the area of our study, the peatland surfaces of the three sites are covered by different plant communities, which have been mentioned in the method presented in chapter 2. Moreover, in different years, the actual evapotranspiration of the three sites are also different.

The manipulated parameters are reduced from eight to four (C , ETr , AI and $A2$). Theoretically, the fitting of GWT at decreasing phase becomes more accurate by considering the effect of ET variations. These parameters were repeatedly adjusted until the optimum simulation result was attained (using the trial and error method). The variation range and adjust step of each parameter value are shown in Table 4-1. Chi-square error (CHI), absolute error (AE) and correlation coefficient (r) are used as criteria for evaluating the simulation result.

Table 4-1. Simulation principle by modified PTM using GWT data of Genseikaen, Sarobetsu Mire

Fixed or Automatically Determined Parameters	Manipulated Parameters	Change Range	Adjust Step
$HA1$	C	C : 1 and above	C : 0.5
$HA2$	ETr	ETr : 0.1 and above	ETr : 0.1
$HA3$	AI	AI : 0.0001 and above	AI : 0.0001
$A3$	$A2$	$A2$: 0.01 and above	$A2$: 0.01

Rule *1: $HA1 = HA2 - 40\text{cm}$, $HA3 = HA2 + 10\text{ cm}$ or $HA3 = \text{GSE}$ (if $(HA2 + 10\text{ cm}) > \text{GSE}$, GSE: ground surface elevation).

Rule *2: $HA2$ equals the value of upper tertile of GWT data that calculated by the following steps. In the first step, all observed GWT data within the calculation period at each site were sorted numerically, in descending order. This set should include every datum, even if there were overlaps. Then, the value found one third of the way down from the maximum value of the organized data set is defined as the upper tertile.

Rule *3: In all cases, $A3 = 1$.

4.3 Results and Discussion

4.3.1 Accuracy improvement by the modified PTM

Fig. 4-1 shows the accuracy improvement of the PTM before and after modification. Based on the AE comparison of the simulation result, it is seen that the simulation accuracy is improved by using the modified PTM. The objective of AE reduction is achieved in all the simulations and the average reduction of AE is significant. In all the three sites, the maximum AE reduction can be enumerated as 0.48cm (at Site E, 1987), 0.57cm (at Site W, 1997) and 1.36cm (at Site WB, 1994).

Figure 4-2 shows the best simulation results (in terms of the absolute errors) at each site by the modified PTM (left row) and the corresponding years' simulation results by the original PTM (right row). Figure 4-3 shows the worst simulation results at each site by the modified PTM (left row) and the corresponding years' simulation results by the original PTM (right row). Table 4-2 shows the absolute errors of the best and the worst simulation results and the average errors of all the simulation results by the original PTM and the modified PTM. The best simulation results using modified PTM are in 1983 for sites E (AE = 0.40cm) and W (AE = 0.38cm), in 2009 for Site WB (AE = 0.57cm). For the worst simulation results using original PTM and modified PTM, except for the result of Site W by modified PTM (AE = 0.88cm), the AEs of sites E and WB are larger than 1cm and less than 3.3cm. In the simulation results both by using original PTM and modified PTM, the worst results of Site E occurred in 1996 and the worst results of Site WB occurred in 2003. It is pointed out that the specific GWT rise was found when there was rainfall for site E at year 1996 and for site WB at year 2003. Its case is unknown. As a consequence, the simulation results by using the

modified PTM cannot match well with the observed GWT fluctuation for these two cases. But, as a whole, by considering the ET variation, the simulation error of PTM is reduced by 17.6%, 23.4% and 30.1% for sites E, W and WB respectively (Table 4-2).



Fig. 4-1 Absolute Error improvement by modified PTM

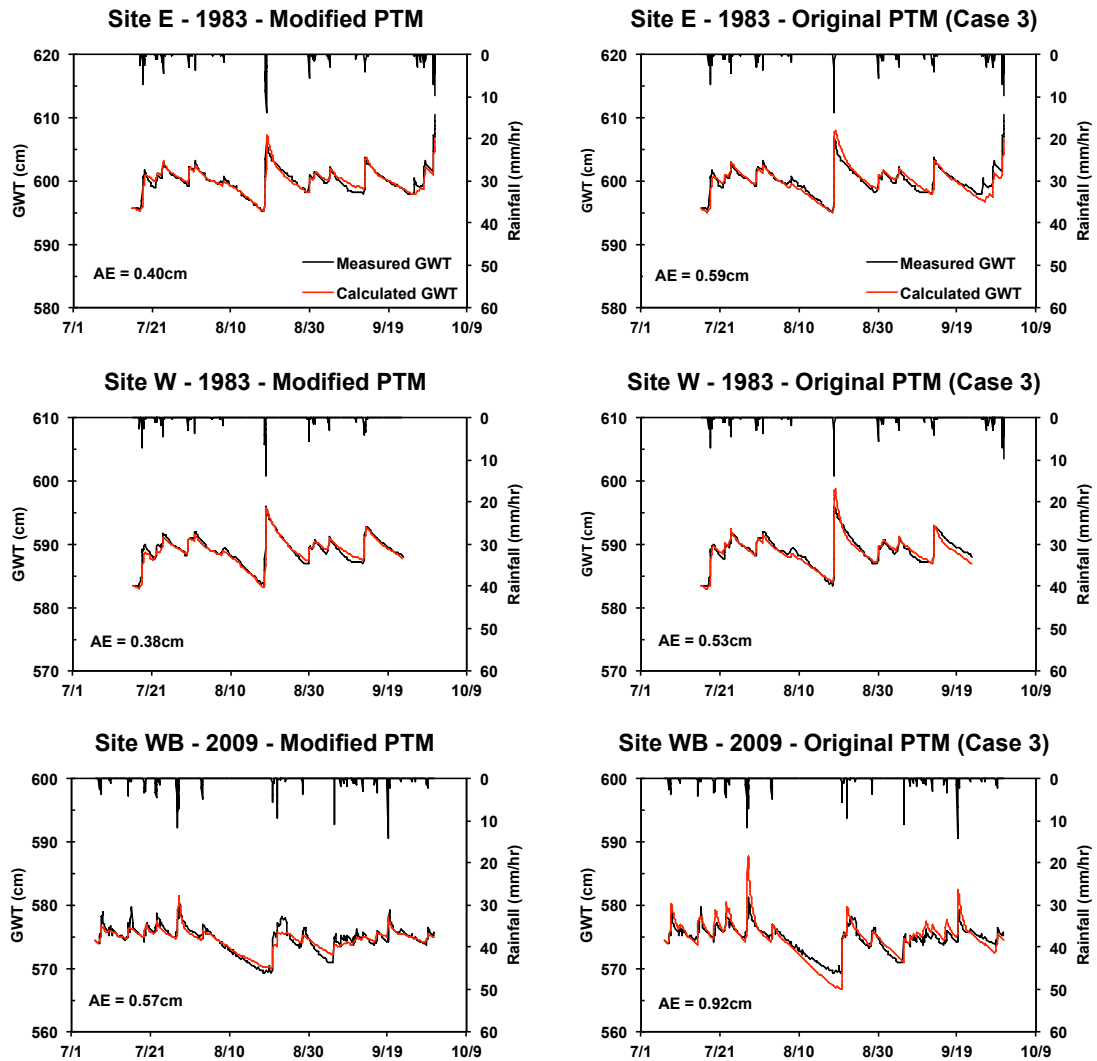


Fig. 4-2 The best simulation results by the modified PTM and the corresponding years' simulation results by the original PTM

Left row: the best simulation results at each site by the modified PTM

Right row: the corresponding years' simulation results at each site by the original PTM

AE: absolute error

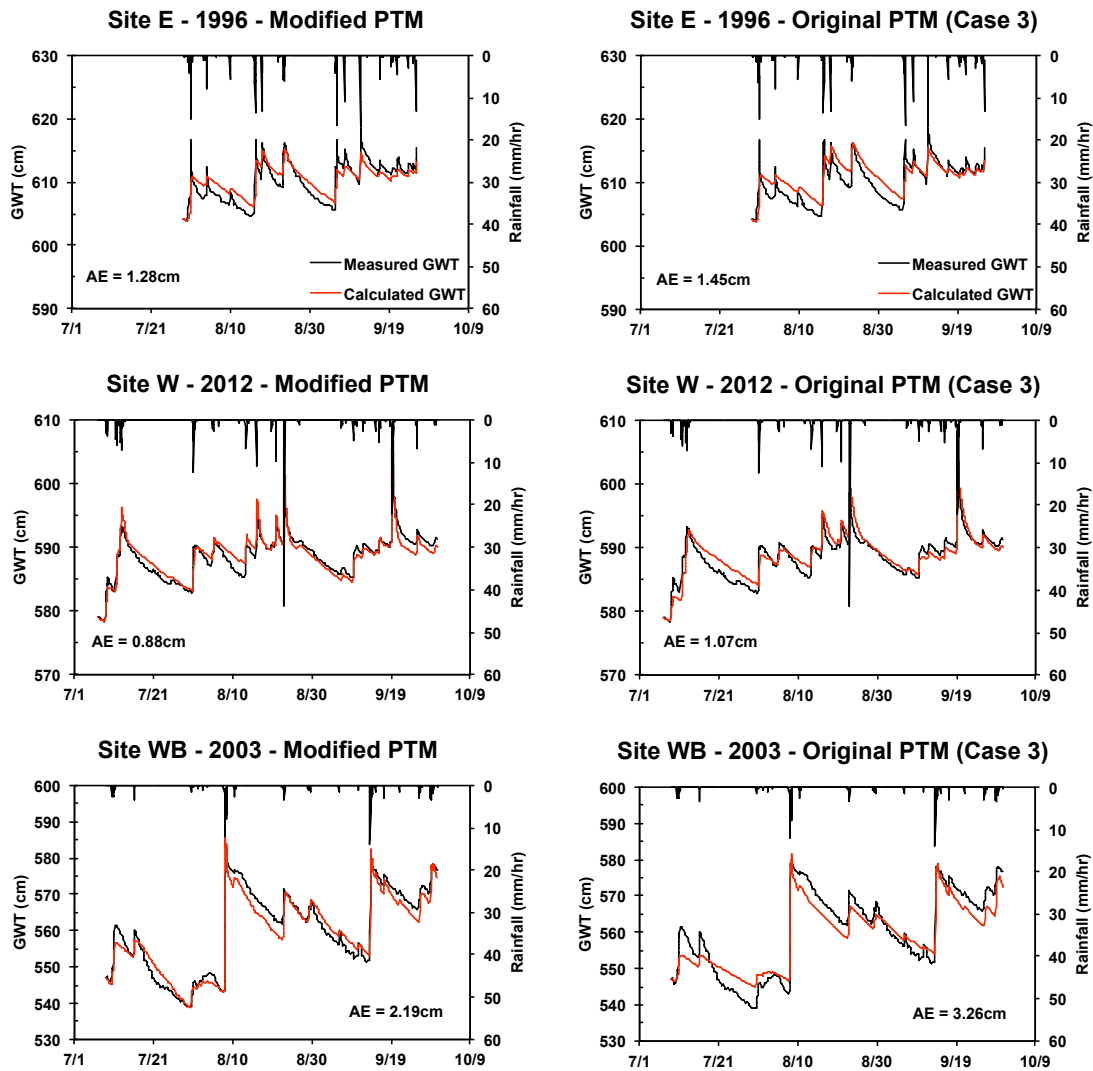


Fig. 4-3 The worst simulation results by the modified PTM and the corresponding years' simulation results by the original PTM

Left row: the worst simulation results at each site by the modified PTM

Right row: the corresponding years' simulation results at each site by the original PTM

AE: absolute error

Table 4-2 Simulation errors of the original and modified PTM

Site	Model used for simulation	Min. AE	Max. AE	Ave. AE
E	Original PTM	0.49	1.45	0.91
		(2002)	(1996)	
	Modified PTM	0.40	1.28	0.75
		(1983)	(1996)	
	Percentage of accuracy improvement	18.4%	11.7%	17.6%
W	Original PTM	0.42	1.21	0.77
		(1996)	(1987)	
	Modified PTM	0.38	0.88	0.59
		(1983)	(2012)	
	Percentage of accuracy improvement	9.5%	27.3%	23.4%
WB	Original PTM	0.90	3.26	1.86
		(2002)	(2003)	
	Modified PTM	0.57	2.19	1.30
		(2009)	(2003)	
	Percentage of accuracy improvement	36.7%	32.8%	30.1%

AE: absolute error (cm); Min.: minimum; Max.: maximum; Ave.: average

Parenthesis: simulation results' year

4.3.2 Effect of improvement by modified PTM

Generally speaking, the fitting of the simulated and the actual GWT fluctuation curves becomes much better by employing the modified PTM. The improvement of simulation accuracy using the modified PTM is seen from the good fitting during both modest (where the slope of GWT is comparatively flat) and drastic (where the slope of GWT becomes sharp) GWT fluctuations.

To be specific, on one hand, the sharp peak of the GWT fluctuation curve is well fitted by using the modified PTM. For instance, based on the conclusion of the chapter 2, the GWT fluctuations at site WB are the most drastic among the three sites. The degree of peat soil decomposition at site WB is slightly higher than the other two sites. Correspondingly, the water storage capacity of peat at Site WB is lower. Thus, as the GWT approaches the peat surface, the evapotranspiration becomes more intensive. This results in sharper decrease of GWT. By considering the effects of evapotranspiration, this sharper decrease of GWT is reproduced with good accuracy (e.g. 1992 at Site W and 1992 at Site WB).

On the other hand, the simulation of the depression of GWT fluctuation curve also becomes more accurate by using the modified PTM. In most cases, the slope of GWT fluctuations is very smooth in the vicinity of valleys. The original PTM expresses the basic water loss including the discharge (discharge to surrounding topographically lower areas and infiltration) and the evapotranspiration by using only one parameter AI . However, discharge and evapotranspiration are two different physical processes. In principle, the former refers to the discharge from the peat layer above HAI ; while, the latter represents the water loss from the peat surface. They characterize the water loss at different height of peat layers with different physical mechanism. Consequently, The

effects of their variations on the GWT fluctuation are different and different parameters should be used to separately characterize the two processes. In view of the above discussion, the integration of the two processes of the basic water loss in the original PTM is inappropriate for characterizing the GWT fluctuations, especially for low peat layers. In contrast, a new parameter ET is introduced to separate the evapotranspiration from the basic water loss in the modified PTM. In this way, the value of AI becomes smaller since it only expresses the basic water loss. This will be further discussed in the following part of this chapter. Thus, with a smaller AI , the slope of GWT fluctuation at lower peat layer becomes flatter and the simulated GWT becomes more accurate (e.g. 1995 at Site W).

When the observed GWT drops, the curve of the water table drawdown is not always smooth and usually shows stepwise fall curve (such as the measured GWT fluctuation curves in 1983 of Site E and 1994 of Site WB shown in Fig. 4-4 and Fig. 4-5). The stepwise water table fall could be interpreted as the consequence of the influence of evapotranspiration variation (Heikurainen 1963; Umeda and Inoue 1985). In the simulation using original PTM, the stepwise GWT fall could not be expressed well (the simulation results by the original PTM in Fig. 4-4 and Fig. 4-5). Consequently, it is difficult to reproduce the subtle part of the GWT fluctuation and results in larger simulation errors than the simulation results using the modified PTM.

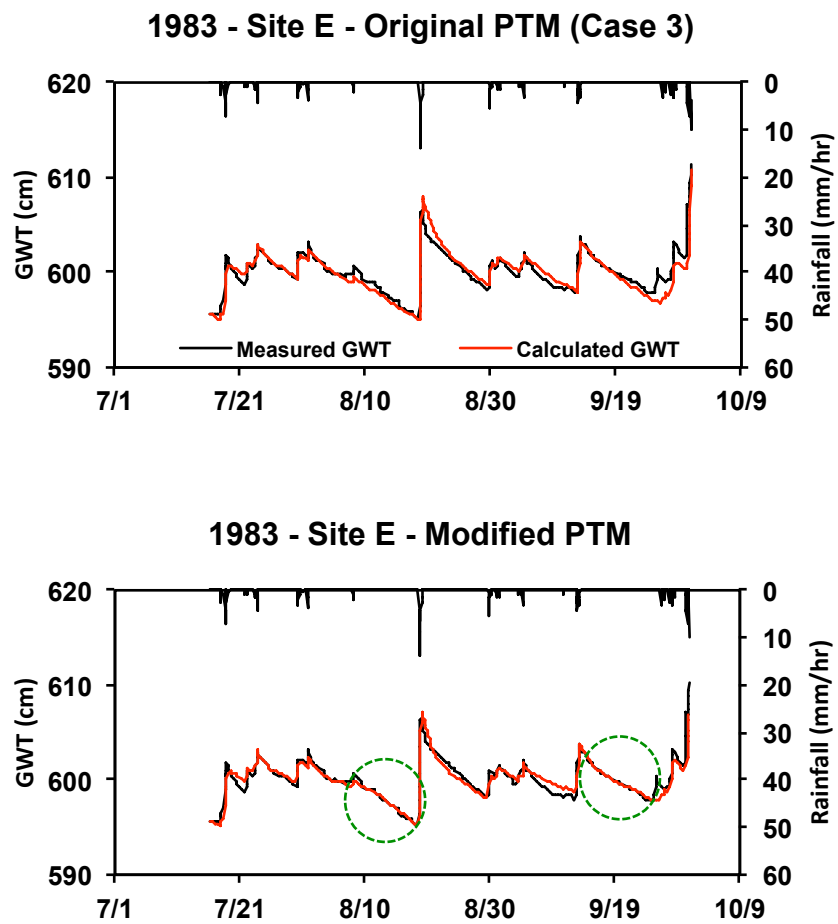


Fig. 4-4 The accuracy improvement on the stepwise fall curves of the GWT fluctuation of Site E in 1983

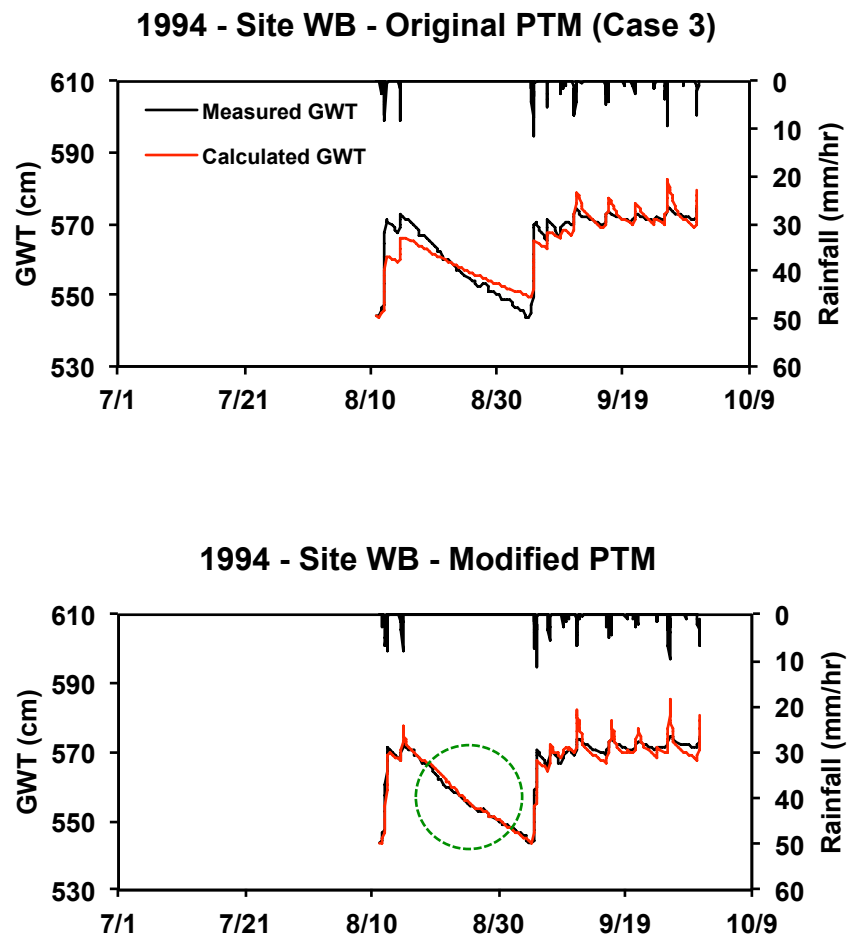


Fig. 4-5 The accuracy improvement on stepwise fall curves of the GWT fluctuation of Site WB in 1994

4.3.3 Parameters of the optimum simulation results by using the modified PTM

Using the simulation principle shown in Table 4-1, the optimum simulation result for each site and each year at Sarobetsu Mire is obtained (shown in Appendix Fig. 3. and Appendix Table 5). The variations of four manipulated parameters from 1983 to 2013 are shown in Fig. 4-6. The average values of parameters in the optimum simulation result by modified PTM and the average values of parameters in the simulation result by Case 3 of original PTM are shown in Table 4-3.

a. C for modified PTM

The C values of Site WB are larger than those of Site E and W (except for 2009). Meanwhile, C values of Site W are larger than or equal to that of Site E (except for 1999). This fact is similar to the simulation result by Case 3 of the original PTM. It indicates that the response of GWT rise to rainfall and response of GWT drop to evapotranspiration among three sites covered by different vegetation are different and in the descending order of Site WB > Site W > Site E.

The average values of parameter C of Site E, W are 1.7 and 2.1. They are smaller than those of the simulation results by using original PTM (Table 4-3). However, the average C value of Site WB is 5.1 and is larger than that of the simulation results by using original PTM. For the three sites, the difference of C values between the original PTM and the modified PTM are not significant ($P > 0.05$). This can be explained by the usage of only one parameter C for the description of GWT responses to both the rainfall and the evapotranspiration. Theoretically, parameter C characterizes the effective porosity of peat soil for water storage.

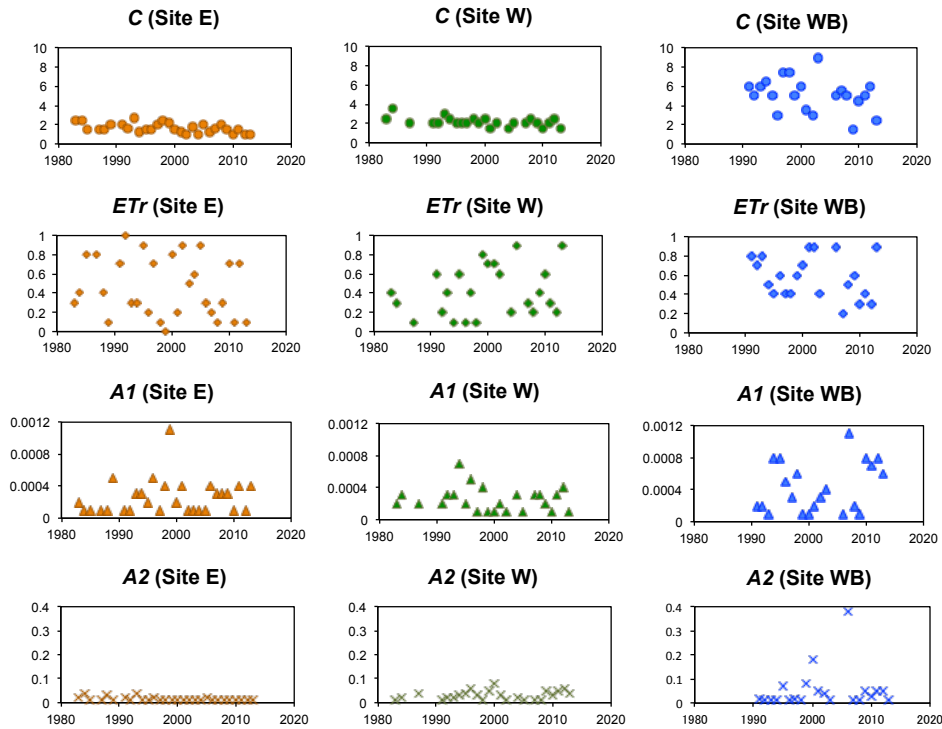


Fig. 4-6 Parameter variations by modified PTM at Genseikaen, Sarobetsu Mire

Table 4-3 Comparison of parameter average value between original PTM and modified PTM

	Site E			Site W			Site WB		
	<i>C</i>	<i>AI</i>	<i>A2</i>	<i>C</i>	<i>AI</i>	<i>A2</i>	<i>C</i>	<i>AI</i>	<i>A2</i>
Original PTM	1.9	0.0005	0.01	2.3	0.0006	0.02	4.3	0.0012	0.03
Modified PTM	1.7	0.0003	0.01	2.1	0.0003	0.03	5.1	0.0004	0.05

*Parameter values obtained by the simulation Case 3 of original PTM

Nonetheless, the evapotranspiration includes the evaporation of water through peat surface and the transpiration of water through the plants. In nature, the features of these two processes are different. Therefore, the effect of evapotranspiration on GWT fluctuation is not solely determined by the characteristics of peat soil, which is unlike the effect of rainfall. To be precise, the expression $C \times ET_r \times ET$ of equation 4-2 should be modified by replacing C with another new coefficient. This is the reason why the average values of C show different trends in the simulations using the original and the modified PTM. However, it is pointed out that the usage of a single parameter C in the proposed method does not apparently affect the simulation accuracy. This is proven by the simulation results. Furthermore, the usage of single parameter C contributes to simplify the computations in the simulation.

b. ET_r for modified PTM

The average value of ET_r at Site E (0.46) is smaller than that at Site WB (0.58) and is larger than that at Site W (0.42). Fig. 4-7(a) shows the value of the ratio of ET (denoted as ET_r) and Fig. 4-7(b) shows the calculated value of ET . In these two figures, comparisons are made between Sites W, WB and Site E. The values of ET_r and ET at Site E are plotted by using a black color straight line whose slope is equal to 1 in Fig. 4-7(a) and Fig. 4-7(b) respectively. Since the x-axis represents the values of ET_r (in Fig. 4-7(a)) or ET (in Fig. 4-7(b)) at Site E, the points above the straight line indicates that the value of ET_r (in Fig. 4-7(a)) or ET (in Fig. 4-7(b)) is larger than that at Site E. Most of the ET_r values and the actual ET at Site E are larger than Site W but smaller than Site WB. This may be caused by the differences of their vegetation coverage. Some of the literature (Fujimoto *et al.* 2006; Umeda 1980) has mentioned that the ET will change when bog vegetation invaded by *Sasa* community.

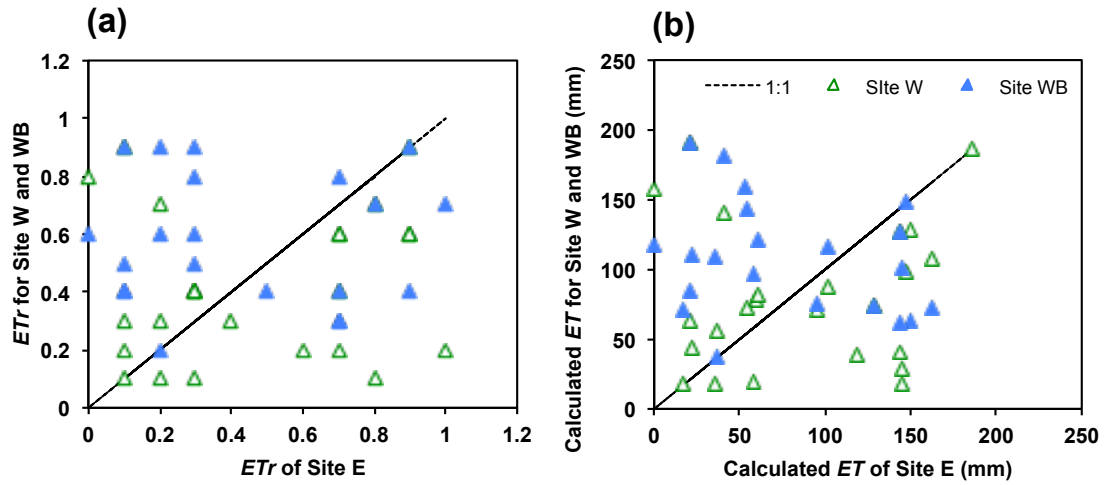


Fig. 4-7 Comparison of ET_r and calculated ET among three

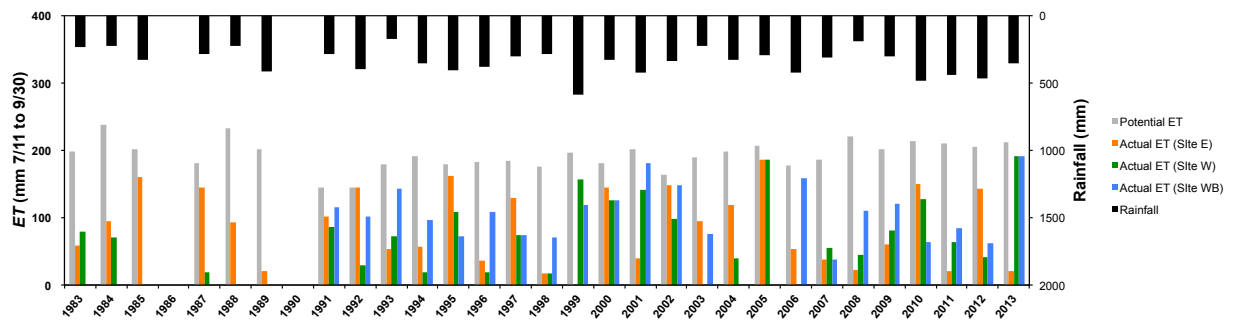


Fig. 4-8 Potential ET and actual ET at Genseikaen, Sarobetsu Mire

No bar means there is missing observation.

In our study, it is difficult to judge the effect of invasion of *Sasa* community to *Sphagnum* community on the variation of *ET*.

In theory, the evapotranspiration of peatland covered by vegetation is not equal to the potential evapotranspiration. This is illustrated by our simulation results, except for two special cases of $ETr = 1$ (1992 at Site E) and $ETr = 0$ (1999 at Site E). $ETr = 1$ indicates the equivalence of the theoretical evapotranspiration and the actual evapotranspiration; while $ETr = 0$ means exactly no evapotranspiration. In later case, it is impossible. But the former case (even if ETr value larger than 1.0) could be happen, it may occur in certain occasion with enough water supply.

Based on the results of GWT simulation by using the modified PTM, the actual *ET* (July to September) of the three sites can be estimated (Fig. 4-8). Disregarding the years with missed data, there are 10 years' measurements of high *ET* (90 mm to 160mm) and 11 years' measurements of low *ET* (10 mm to 90mm) at Site E. Similarly, the number of years with high *ET* measurements at sites W and WB is 6 and 11 respectively. And, the number of years with low *ET* measurements at sites W and WB is 12 and 7 respectively. It is noted that, the *ETs* at Site E and Site WB are generally higher than Site W.

c. *AI* for modified PTM

The values of parameter *AI* are nearly the same at sites E and W and they become larger at site WB (Fig. 4-9). This means the basic water loss of the peat at Site E and Site W is similar and the basic water loss is more significant at Site WB. It is noticed that the values of *AI* used in modified PTM are generally smaller than those obtained by using the original PTM, except for year 1989, 1998, 1999 of site E

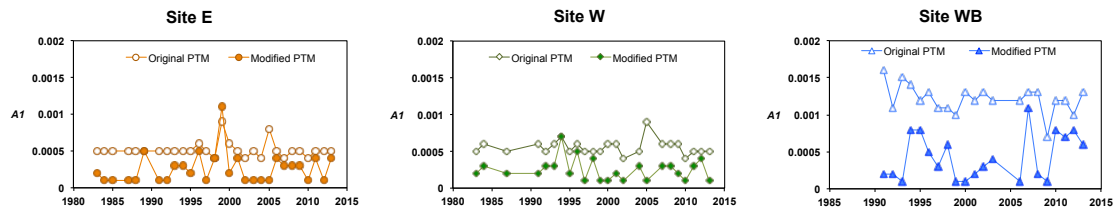


Fig. 4-9 Comparison of $A1$ between original PTM and modified PTM

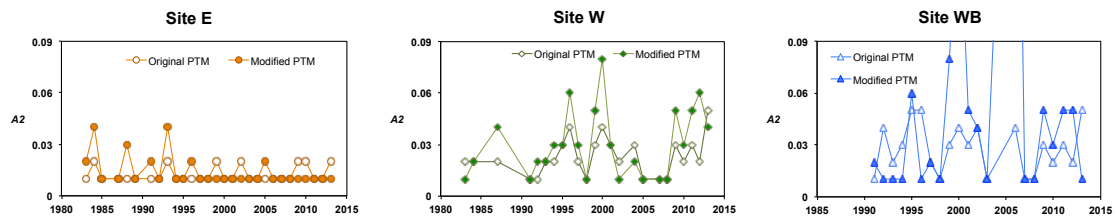


Fig. 4-10 Comparison of $A2$ between original PTM and modified PTM

and year 1994 of site W (Fig. 4-9). The decrease of values of $A1$ is mainly caused by the introduction of new parameter ET into the PTM. In fact, ET is introduced to separate the evapotranspiration from the GWT drop in the modified PTM. In this way, the value of $A1$ becomes smaller since it only expresses the basic water loss. This modification contributes to improve the simulation accuracy because the basic water loss and the evapotranspiration are intrinsically two different physical processes that occur at different heights of peat layers with different physical mechanisms.

d. $A2$ for modified PTM

In the modified PTM, the values of parameter $A2$ are almost the same as those obtained by using the original PTM (Fig. 4-10). As defined in the previous chapters, $A2$ is the size of the plughole at the height of $HA2$ on the side-wall of water tank. Thus, it represents the water loss from the peat layer above $HA2$. Due to such a height, $A2$ is directly affected by neither the evapotranspiration at peat surface nor the basic water loss below $HA3$. As a result, the numerical values of $A2$ are also not changed to a large extent when the effects of evapotranspiration are taken into consideration. This can be seen from the values of $A2$ at sites E and W. The discrepancies of the $A2$ values can be seen from the response of 1999 ($A2 = 0.08$), 2000 ($A2 = 0.18$) and 2006 ($A2 = 0.38$) at site WB (can not show in Fig. 4-10 due to the large value). This is not surprising because drastic variations of GWT can be experienced and occasional malfunctions of measurement instrument are possible.

4.3.4 Relationship between parameter C and rainfall

The relationship between parameter C and rainfall has been previously discussed in chapter 2. Negative correlation is discovered in parameter C and the rainfall during the calculation period by using original PTM. However, by considering the effect of evapotranspiration, this relationship becomes inconspicuous as illustrated in Fig. 4-11. Obviously, the coefficient of determination R^2 becomes smaller compared with the results by using original PTM (Fig. 2-10). This can be explained by equation 4-2 where C is used to quantitatively express the response of GWT change to both rainfall and the evapotranspiration. The usage of C as a composite coefficient for describing the response of GWT change to external inflow and outflow will automatically modify its value. As a consequence, the numerical relationship between the modified C and the rainfall becomes less obvious than the case by using the original PTM.

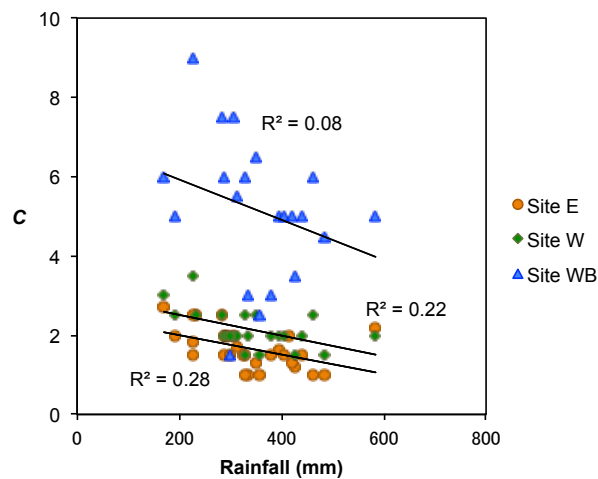


Fig. 4-11 Relationship between C and Rainfall

4.4 Conclusion

This chapter presents a modified PTM by considering the effects of evapotranspiration on the GWT fluctuations. Detailed explanations are given on the estimation of evapotranspiration by using the available data samples. The merit of simplicity of the proposed PTM evaluation method is maintained since only one term is incorporated into the original PTM. Due to the modification, the effects of basic water loss and evapotranspiration are separated. Consequently, better simulation accuracy is obtained by using the proposed modification. Simulations for GWT fluctuation have been implemented at the three sites of E, W and WB by using the modified PTM and the results are presented and compared with the results of the original PTM. The improvement of simulation accuracy is obvious at the peaks and the depression of GWT fluctuation curve. Of course, the proposed modification affects the numerical values of some parameters used by the original PTM. However, this modification does not change the characteristics of the GWT fluctuation and profile of the parameter variations. Instead, the overall improvement of simulation accuracy is obvious by employing the modified PTM. Discussions are made on the variations of these parameters and in-depth analyses are made based on the physical meanings of some parameters.

CHAPTER 5

General conclusion

This study mainly focuses on the evaluation of GWT fluctuations in peatland hydrological system. The fundamentals of peatland ecosystem and the importance of peatland hydrology are firstly discussed. Then, a simple but effective evaluation method based on PTM is proposed for the research and analysis of peatland hydrological conditions spotted from GWT. Further improvements are made to extend the applicable range and to increase the accuracy of the proposed method. The conclusions and contributions of this study are summarized below.

In the first place, the proposed PTM based method is employed to evaluate the shallow GWT fluctuations of bogs. It numerically expresses the GWT fluctuation patterns through the usage of PTM parameters. The meanings and impacts of different PTM parameters are discussed to yield a better understanding of the proposed method. Then, mathematical analysis is given to show the functionality of PTM model. It is seen from the mathematical analysis that the proposed method only requires the inputs of GWT and rainfall and is very simple in structure. In the next step, simulations are carried out to verify the efficacy of the proposed method by using absolute GWT height (with reference to sea level). In the simulations, 29 years' GWT data (sampled from Sarobetsu Mire, Hokkaido, Japan) are utilized. By comparing the simulation results with the practical measurements, it is concluded that a good simulation accuracy of less than a few centimetres is achieved by using the proposed method. To further investigate the simplification of computational structure and the improvement

of accuracy for the proposed method, in-depth analyses and discussions are carried out based on simulations. Simulation rules are established to appropriately reduce the number of parameters without degrading the performance of the proposed method.

Secondly, in view of the usage of absolute GWT height in the original proposal, an approach is developed to further extend the applicability of the proposed PTM based method. This approach contributes to make the proposed method compatible to the GWT data that do not have a reference height. Generally, such type of data has no common meaning or information with respect to the ground surface or sea level. Therefore, they can not be directly used in many evaluation methods proposed by the other researchers. In this study, trials are made to interpret and analyze the GWT fluctuation patterns by using the coefficient of GWT increase and the vertical distances between groundwater plugholes instead of using the heights of groundwater plugholes. The feasibility of this approach is testified through simulations using the 29 years' GWT data (sampled from Ochiai, Sarobetsu Mire, northern Hokkaido, Japan) without absolute height reference. It is shown that the coefficient of GWT increase and the vertical distances between groundwater plugholes have successfully characterize the spatial and temporal variations of peatland hydrological conditions.

Thirdly, in concern of further improvement of evaluation accuracy of the proposed method, an approach is proposed in chapter 4 to incorporate the effects of evapotranspiration into the original PTM model. According to the mathematical analysis, this approach contributes to separate the effects of basic water loss and the evapotranspiration. It maintains nearly all the merits of the original model while obtaining greater accuracy. Simulations are carried out by using this approach and the results are compared with those obtained by using the original PTM based method.

Comparative analyses have clearly shown that the proposed approach modifies the original PTM based method in a simple way, but provides superior performance from the viewpoint of accuracy. Therefore, it can be concluded that the proposed approach is valid and should be adopted.

In summary, this study has proposed a new PTM based method to evaluate the GWT fluctuations in peatland hydrological system. Efforts are taken to further improve the applicability and accuracy of the proposed method. Simple mathematical structure, small number of required measurements and good simulation accuracies are observed by using the proposed method. Thus, it is reasonable to conclude that our proposal is very meaningful for the research in peatland hydrology, especially when monitoring cost and computational complexity are concerned. To better illustrate the principles and applications of the proposed method, comprehensive analyses and discussions are provided in this thesis.

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APPENDIX TABLES

Table 1. Parameter values of the Case 3 by PTM, Genseikaen, Sarobestu Mire

Year	Site E			Site W			Site WB		
	C	A1	A2	C	A1	A2	C	A1	A2
1983	2.6	0.0005	0.01	3.0	0.0005	0.02			
1984	2.7	0.0005	0.02	3.0	0.0006	0.02			
1985	1.7	0.0005	0.01						
1987	2.4	0.0005	0.01	2.7	0.0005	0.02			
1988	2.7	0.0005	0.01						
1989	1.7	0.0005	0.01						
1991	2.2	0.0005	0.01	2.6	0.0006	0.01	5.8	0.0016	0.01
1992	1.7	0.0005	0.01	1.8	0.0005	0.01	3.5	0.0011	0.04
1993	2.8	0.0005	0.02	3.3	0.0006	0.02	6.5	0.0015	0.02
1994	1.5	0.0005	0.01	2.2	0.0007	0.02	4.3	0.0014	0.03
1995	1.6	0.0005	0.01	1.8	0.0005	0.03	3.5	0.0012	0.05
1996	1.6	0.0006	0.01	1.9	0.0006	0.04	3.7	0.0013	0.05
1997	2.1	0.0005	0.01	2.6	0.0005	0.02	5.2	0.0011	0.02
1998	2.4	0.0004	0.01	2.9	0.0005	0.01	6.2	0.0011	0.01
1999	1.9	0.0009	0.02	1.5	0.0005	0.03	2.7	0.001	0.03
2000	1.6	0.0006	0.01	2.2	0.0006	0.04	4.5	0.0013	0.04
2001	1.3	0.0005	0.01	1.9	0.0006	0.03	3.3	0.0012	0.03
2002	1.5	0.0004	0.02	2.1	0.0004	0.02	4.4	0.0013	0.04
2003	2.8	0.0005	0.01				6.1	0.0012	0.01
2004	1.4	0.0004	0.01	2.2	0.0005	0.03			
2005	2.2	0.0008	0.01	2.4	0.0009	0.01			
2006	1.3	0.0005	0.01				3.4	0.0012	0.04
2007	1.8	0.0004	0.01	2.4	0.0006	0.01	4.7	0.0013	0.01
2008	2.9	0.0005	0.01	3.4	0.0006	0.01	6.3	0.0013	0.01
2009	1.9	0.0005	0.02	2.3	0.0006	0.03	3.5	0.0007	0.03

2010	1.5	0.0004	0.02	1.5	0.0004	0.02	3	0.0012	0.02
2011	1.6	0.0005	0.01	1.8	0.0005	0.03	3.2	0.0012	0.03
2012	1.5	0.0005	0.01	1.8	0.0005	0.02	3.1	0.001	0.02
2013	1.6	0.0005	0.02	1.7	0.0005	0.05	4.0	0.0013	0.05
Ave.	1.9	0.0005	0.01	2.3	0.0006	0.02	4.3	0.0012	0.03

Table 2. Parameter values of the Case 4 by PTM, Genseikaen, Sarobestu Mire

Year	Site E		Site W		Site WB	
	<i>C</i>	<i>HA2-HA1</i>	<i>C</i>	<i>HA2-HA1</i>	<i>C</i>	<i>HA2-HA1</i>
1983	2.6	81	3.0	96		
1984	2.7	98	3.0	114		
1985	1.7	93				
1987	2.4	94	2.7	62		
1988	2.7	90				
1989	2	106				
1991	2.4	102	2.6	115	5.8	250
1992	1.5	80	1.8	71	3.6	200
1993	2.9	103	3.3	116	6.5	213
1994	1.5	92	2.2	127	4.3	230
1995	1.6	98	1.8	103	3.5	220
1996	1.6	123	1.9	136	3.0	240
1997	2.1	84	2.5	75	5.2	185
1998	2.4	79	2.9	93	6.2	190
1999	1.9	164	1.5	102	2.6	180
2000	1.6	100	2.2	140	4.5	286
2001	1.3	95	1.9	124	3.3	227
2002	1.5	74	2.1	80	4.4	229
2003	2.6	82			6.3	195
2004	1.5	69	1.8	87		
2005	2.2	139	2.4	148		
2006	1.3	92			3.4	220
2007	1.8	71	2.4	98	4.7	194

2008	2.9	86	3.4	109	6.3	220
2009	2	98	2.3	109	3.5	130
2010	1.5	75	1.5	81	3.1	195
2011	1.6	84	1.8	95	3.2	200
2012	1.5	86	1.8	99	3.1	156
2013	1.6	117	1.7	129	3.2	220
Ave.	2.0	95	2.3	105	4.3	209

Table 3. Parameter values of the Case 1 by PTM, Ochiai, Sarobetsu Mire

Year	Site D			Site M			Site U		
	C	A1	A2	C	A1	A2	C	A1	A2
1983	4.0	0.0020	0.04	2.9	0.0019	0.04			
1984	4.0	0.0021	0.02				2.7	0.0018	0.02
1985	3.5	0.0020	0.02	2.5	0.0024	0.02	2.4	0.0020	0.02
1986	4.8	0.0020	0.004	4.4	0.0018	0.008	4.0	0.0010	0.007
1987	4.2	0.0024	0.03	2.8	0.0015	0.025	2.7	0.0014	0.02
1988	4.2	0.0027	0.15	3.5	0.0023	0.06	3.3	0.0022	0.05
1989	3.4	0.0050	0.04	2.8	0.0030	0.04	2.2	0.0021	0.03
1990	3.3	0.0040	0.04	2.7	0.0017	0.04	2.1	0.0014	0.03
1991	4.1	0.0025	0.02	4.0	0.0018	0.02	3.5	0.0018	0.02
1992	3.8	0.0030	0.01	3.1	0.0018	0.01	2.9	0.0015	0.002
1993	5.3	0.0025	0.02	5.2	0.0020	0.02	5.0	0.0020	0.02
1994	4.1	0.0025	0.02	3.5	0.0020	0.02	3.0	0.0020	0.06
1995	3.6	0.0045	0.04	3.2	0.0022	0.04	2.6	0.0017	0.04
1996	3.7	0.0030	0.06	3.0	0.0017	0.06	2.5	0.0014	0.05
1997	4.2	0.0024	0.03	3.2	0.0015	0.02	2.0	0.0012	0.02
1999	2.8	0.0070	0.06	1.5	0.0020	0.06	1.2	0.0012	0.06
2000	4.0	0.0020	0.02	3.2	0.0020	0.02	2.6	0.0016	0.02
2001	3.9	0.0025	0.06	2.2	0.0013	0.06	1.5	0.0012	0.05
2002	4.0	0.0021	0.06	2.8	0.0013	0.06	2.5	0.0010	0.05
2003	4.4	0.0026	0.06	4.2	0.0020	0.03	3.0	0.0010	0.015
2004	3.8	0.0030	0.04	3.0	0.0010	0.04	2.3	0.0011	0.04

2005	4.0	0.0033	0.02	3.2	0.0020	0.02	2.5	0.0018	0.02
2006	3.1	0.0027	0.06	2.5	0.0020	0.05			
2007	4.0	0.0030	0.04	3.5	0.0020	0.03			
2008	5.0	0.0025	0.03	3.5	0.0016	0.01			
2009	4.2	0.0027	0.04	3.5	0.0020	0.03			
2010	3.0	0.0022	0.05	1.9	0.0018	0.04			
2011	3.3	0.0029	0.08	2.5	0.0019	0.06			
2012	2.9	0.0025	0.08	2.3	0.0016	0.06			
Ave.	3.9	0.0029	0.04	3.1	0.0019	0.04	2.7	0.0015	0.03

Table 4. Parameter values of the Case 2 by PTM, Ochiai, Sarobetsu Mire

Year	Site D			Site M			Site U		
	C	HA2-HA1	HA3-HA2	C	HA2-HA1	HA3-HA2	C	HA2-HA1	HA3-HA2
1983	3.5	18.8	10.0	3.1	13.6	10.0			
1984	3.9	21.1	13.9				2.7	15.0	5.0
1985	4.5	23.5	11.5	2.2	19.1	10.0	1.9	17.0	3.0
1986	6.0	25.7	17.3	5.0	22.0	17.0	4.5	18.0	10.0
1987	4.0	26.4	13.6	3.5	22.3	15.7	3.0	19.3	7.7
1988	4.4	29.7	8.3	3.8	25.1	7.9	3.7	21.0	7.0
1989	3.1	35.4	31.6	2.4	28.1	10.0	2.3	25.0	10.0
1990	3.8	32.5	21.5	2.3	22.3	10.0	1.8	18.8	9.2
1991	4.8	31.1	14.9	4.0	22.7	13.3	3.5	20.4	11.6
1992	4.0	27.4	13.6	3.2	20.0	10.0	2.8	18.4	7.6
1993	5.5	29.0	10.0	5.5	19.6	10.0	5.2	16.6	10.0
1994	5.0	32.6	13.4	3.3	24.9	10.0	3.0	21.2	10.0
1995	3.6	33.8	17.2	3.1	27.0	9.0	2.5	23.7	6.3
1996	3.7	34.7	13.3	2.2	26.0	6.0	1.5	21.3	2.7
1997	4.7	32.4	23.6	3.3	18.2	10.8	2.0	12.4	10.0
1999	2.8	36.2	12.8	2.2	26.3	4.7	1.5	16.9	5.1
2000	4.2	33.3	15.7	2.8	23.0	5.0	2.0	15.0	3.0
2001	3.9	33.4	10.0	2.2	20.0	4.0	1.6	15.3	5.7
2002	5.0	21.5	20.5	2.4	20.3	2.7	1.6	12.4	3.6

2003	4.4	26.8	18.2	4.4	20.9	10.0	2.8	14.0	8.0
2004	4.4	30.7	28.3	2.8	19.2	4.8	1.8	13.1	10.0
2005	3.4	34.4	22.6	2.7	26.0	7.0	2.0	20.0	15.0
2006	3.0	31.9	12.1	2.2	25.8	6.2			
2007	3.8	29.3	15.7	2.6	21.8	11.2			
2008	6.0	27.6	10.0	4.0	18.6	10.0			
2009	4.5	32.8	13.2	3.3	25.6	17.4			
2010	3.3	33.8	17.2	2.4	24.8	10.0			
2011	4.2	34.5	12.5	2.5	25.7	7.3			
2012	3.5	37.0	18.0	2.8	26.7	12.3			
Ave.	4.2	30.3	15.9	3.1	22.7	9.4	2.6	17.8	7.6

Table 5. Parameter values of the optimum results by modified PTM, Genseikaen, Sarobestu Mire

Year	Site E				Site W				Site WB			
	<i>C</i>	<i>A1</i>	<i>A2</i>	<i>ETr</i>	<i>C</i>	<i>A1</i>	<i>A2</i>	<i>ETr</i>	<i>C</i>	<i>A1</i>	<i>A2</i>	<i>ETr</i>
1983	2.5	0.0002	0.02	0.3	2.5	0.0002	0.01	0.4				
1984	2.5	0.0001	0.04	0.4	3.5	0.0003	0.02	0.3				
1985	1.5	0.0001	0.01	0.8								
1987	1.5	0.0001	0.01	0.8	2.0	0.0002	0.04	0.1				
1988	1.5	0.0001	0.03	0.4								
1989	2.0	0.0005	0.01	0.1								
1991	2.0	0.0001	0.02	0.7	2.0	0.0002	0.01	0.6	6.0	0.0002	0.02	0.8
1992	1.6	0.0001	0.01	1.0	2.0	0.0003	0.02	0.2	5.0	0.0002	0.01	0.7
1993	2.7	0.0003	0.04	0.3	3.0	0.0003	0.02	0.4	6.0	0.0001	0.01	0.8
1994	1.3	0.0003	0.01	0.3	2.5	0.0007	0.03	0.1	6.5	0.0008	0.01	0.5
1995	1.5	0.0002	0.01	0.8	2.0	0.0003	0.03	0.5	5.0	0.0007	0.06	0.5
1996	1.5	0.0005	0.02	0.2	2.0	0.0005	0.06	0.1	3.0	0.0005	0.01	0.6
1997	2.0	0.0001	0.01	0.7	2.0	0.0001	0.03	0.4	7.5	0.0003	0.02	0.4
1998	2.5	0.0004	0.01	0.1	2.5	0.0004	0.01	0.1	7.5	0.0006	0.01	0.4
1999	2.2	0.0011	0.01	0	2.0	0.0001	0.05	0.8	5.0	0.0001	0.08	0.6
2000	1.5	0.0002	0.01	0.8	2.5	0.0001	0.08	0.7	6.0	0.0001	0.18	0.7

2001	1.2	0.0004	0.01	0.2	1.5	0.0002	0.03	0.7	3.5	0.0002	0.05	0.9
2002	1.0	0.0001	0.01	0.9	2.0	0.0001	0.01	0.6	3.0	0.0003	0.04	0.9
2003	1.8	0.0001	0.01	0.5					9.0	0.0004	0.01	0.4
2004	1.0	0.0001	0.01	0.6	1.5	0.0002	0.02	0.5				
2005	2.0	0.0001	0.02	0.9	2.0	0.0001	0.01	0.9				
2006	1.3	0.0004	0.01	0.3					5.0	0.0001	0.38	0.9
2007	1.7	0.0003	0.01	0.2	2.0	0.0003	0.01	0.3	5.5	0.0011	0.01	0.2
2008	2.0	0.0003	0.01	0.1	2.5	0.0003	0.01	0.2	5.0	0.0002	0.01	0.5
2009	1.5	0.0003	0.01	0.3	2.0	0.0002	0.05	0.4	1.5	0.0001	0.05	0.6
2010	1.0	0.0001	0.01	0.7	1.5	0.0001	0.03	0.6	4.5	0.0008	0.03	0.3
2011	1.5	0.0004	0.01	0.1	2.0	0.0003	0.05	0.3	5.0	0.0007	0.05	0.4
2012	1.0	0.0001	0.01	0.7	2.5	0.0004	0.06	0.2	6.0	0.0008	0.05	0.3
2013	1.0	0.0004	0.01	0.1	1.5	0.0001	0.04	0.9	2.5	0.0006	0.01	0.9
Ave.	1.7	0.0003	0.01	0.5	2.1	0.0003	0.03	0.4	5.1	0.0004	0.05	0.6

Table 6. The errors of the results of Case 3 by PTM, Genseikaen, Sarobestu Mire

Year	Site E			Site W			Site WB		
	CHI	AE	r	CHI	AE	r	CHI	AE	r
1983	0.0012	0.59	0.93	0.0008	0.53	0.96			
1984	0.0022	0.83	0.95	0.0023	0.88	0.97			
1985	0.0013	0.72	0.93						
1987	0.0033	1.12	0.91	0.0055	1.21	0.87			
1988	0.0037	1.18	0.92						
1989	0.0060	1.32	0.96						
1991	0.0019	0.84	0.93	0.0014	0.75	0.96	0.0069	1.67	0.95
1992	0.0051	1.31	0.92	0.0021	0.82	0.95	0.0073	1.44	0.94
1993	0.0013	0.67	0.93	0.0007	0.47	0.98	0.0111	1.70	0.96
1994	0.0019	0.79	0.95	0.0014	0.71	0.98	0.0213	2.60	0.93
1995	0.0030	1.02	0.94	0.0010	0.59	0.97	0.0068	1.40	0.93
1996	0.0047	1.45	0.89	0.0005	0.42	0.96	0.0037	1.07	0.93
1997	0.0018	0.81	0.97	0.0036	1.14	0.96	0.0124	2.09	0.94
1998	0.0038	1.26	0.93	0.0023	0.90	0.96	0.0201	2.69	0.96

1999	0.0027	0.95	0.97	0.0011	0.57	0.94	0.0172	2.22	0.89
2000	0.0029	1.04	0.89	0.0024	1.01	0.89	0.0138	2.23	0.87
2001	0.0016	0.69	0.95	0.0010	0.55	0.96	0.0040	1.10	0.95
2002	0.0006	0.49	0.97	0.0008	0.59	0.98	0.0026	0.90	0.98
2003	0.0021	0.78	0.96				0.0240	3.26	0.97
2004	0.0010	0.60	0.98	0.0018	0.77	0.95			
2005	0.0039	1.05	0.94	0.0032	1.01	0.97			
2006	0.0008	0.49	0.98				0.0158	2.17	0.85
2007	0.0009	0.55	0.98	0.0018	0.80	0.99	0.0097	1.86	0.99
2008	0.0032	1.21	0.91	0.0024	0.88	0.95	0.0116	2.03	0.95
2009	0.0014	0.69	0.92	0.0014	0.61	0.93	0.0029	0.92	0.93
2010	0.0019	0.83	0.96	0.0024	0.94	0.96	0.0163	1.88	0.95
2011	0.0019	0.80	0.99	0.0021	0.76	0.96	0.0153	2.20	0.96
2012	0.0029	1.09	0.93	0.0028	1.07	0.93	0.0197	2.54	0.88
2013	0.0048	1.35	0.74	0.0009	0.55	0.94	0.0058	1.49	0.89
Ave.	0.0025	0.91	0.94	0.0019	0.77	0.95	0.0118	1.88	0.93

Table 7. The errors of the results of Case 4 by PTM, Genseikaen, Sarobestu Mire

Year	Site E			Site W			Site WB		
	CHI	AE	r	CHI	AE	r	CHI	AE	r
1983	0.0009	0.51	0.94	0.0007	0.52	0.96			
1984	0.0022	0.79	0.95	0.0019	0.79	0.97			
1985	0.0016	0.81	0.92						
1987	0.0035	1.30	0.85	0.0029	0.98	0.92			
1988	0.0045	1.42	0.91						
1989	0.0077	1.45	0.95						
1991	0.0010	0.56	0.94	0.0014	0.78	0.96	0.0089	1.79	0.94
1992	0.0081	1.50	0.90	0.0008	0.54	0.98	0.0133	2.05	0.90
1993	0.0013	0.66	0.93	0.0007	0.48	0.97	0.0094	1.71	0.96
1994	0.0024	0.88	0.94	0.0018	0.81	0.97	0.0288	2.87	0.92
1995	0.0024	0.99	0.94	0.0013	0.66	0.96	0.0103	1.72	0.91
1996	0.0036	1.29	0.89	0.0012	0.67	0.93	0.0052	1.38	0.88

1997	0.0032	1.12	0.96	0.0020	0.78	0.95	0.0149	2.16	0.92
1998	0.0059	1.42	0.90	0.0024	0.96	0.95	0.0220	2.85	0.95
1999	0.0027	0.92	0.97	0.0019	0.79	0.93	0.0284	2.67	0.84
2000	0.0031	1.15	0.85	0.0030	1.08	0.87	0.0136	2.31	0.86
2001	0.0019	0.82	0.94	0.0015	0.68	0.96	0.0046	1.10	0.95
2002	0.0006	0.52	0.97	0.0008	0.57	0.97	0.0061	1.29	0.98
2003	0.0017	0.78	0.93				0.0254	3.38	0.96
2004	0.0013	0.65	0.95	0.0015	0.71	0.96			
2005	0.0041	1.16	0.94	0.0032	1.02	0.96			
2006	0.0014	0.73	0.97				0.0165	2.10	0.86
2007	0.0013	0.64	0.98	0.0028	0.94	0.98	0.0179	2.56	0.97
2008	0.0039	1.19	0.86	0.0029	0.94	0.93	0.0135	2.15	0.95
2009	0.0015	0.73	0.91	0.0016	0.63	0.93	0.0039	1.10	0.93
2010	0.0018	0.81	0.96	0.0022	0.89	0.96	0.0231	2.30	0.92
2011	0.0014	0.72	0.98	0.0031	0.94	0.96	0.0244	2.98	0.92
2012	0.0043	1.37	0.90	0.0028	1.07	0.93	0.0220	2.53	0.86
2013	0.0045	1.36	0.71	0.0013	0.67	0.91	0.0059	1.42	0.91
Ave.	0.0029	0.97	0.92	0.0019	0.79	0.95	0.0151	2.11	0.92

Table 8. The errors of the results of Case 1 by PTM, Ochiai, Sarobestu Mire

Year	Site D			Site M			Site U		
	CHI	AE	r	CHI	AE	r	CHI	AE	r
1983	0.0037	1.15	0.95	0.0027	1.03	0.92			
1984	0.0021	0.64	0.95				0.0039	1.15	0.97
1985	0.0146	2.38	0.86	0.0024	0.84	0.93	0.0012	0.66	0.97
1986	0.0019	0.70	0.96	0.0084	1.66	0.98	0.0028	0.93	0.98
1987	0.0055	1.69	0.96	0.0030	0.95	0.97	0.0034	0.93	0.97
1988	0.0237	2.15	0.88	0.0100	1.94	0.94	0.0069	1.48	0.96
1989	0.0683	5.20	0.87	0.0107	1.79	0.97	0.0093	1.76	0.96
1990	0.0244	2.53	0.93	0.0112	1.78	0.91	0.0062	1.50	0.98
1991	0.0025	0.81	0.98	0.0015	0.63	0.97	0.0059	1.52	0.96
1992	0.0053	1.16	0.96	0.0042	1.27	0.95	0.0021	0.80	0.97

1993	0.0044	1.03	0.99	0.0037	1.01	0.99	0.0028	0.97	0.99
1994	0.0295	2.75	0.93	0.0151	2.32	0.93	0.0133	2.09	0.94
1995	0.0342	3.04	0.88	0.0036	0.94	0.98	0.0039	1.09	0.92
1996	0.0268	2.94	0.67	0.0062	1.41	0.79	0.0026	0.89	0.98
1997	0.0117	1.86	0.94	0.0073	1.20	0.97	0.0116	1.75	0.90
1999	0.0442	3.32	0.91	0.0266	2.35	0.82	0.0203	2.21	0.81
2000	0.0090	1.73	0.94	0.0107	1.57	0.89	0.0083	1.39	0.89
2001	0.0140	1.85	0.94	0.0045	1.09	0.87	0.0050	1.27	0.87
2002	0.0016	0.58	0.99	0.0025	0.79	0.94	0.0022	0.72	0.94
2003	0.0083	1.30	0.96	0.0081	1.27	0.95	0.0022	0.77	0.96
2004	0.0107	1.92	0.95	0.0048	1.06	0.90	0.0021	0.72	0.97
2005	0.0088	1.64	0.97	0.0171	2.14	0.88	0.0046	1.29	0.96
2006	0.0130	1.97	0.92	0.0065	1.40	0.90			
2007	0.0067	1.78	0.96	0.0065	1.79	0.95			
2008	0.0024	0.98	0.98	0.0019	0.97	0.98			
2009	0.0029	1.16	0.95	0.0058	1.82	0.86			
2010	0.0055	1.49	0.96	0.0078	1.93	0.94			
2011	0.0043	1.25	0.98	0.0021	0.91	0.98			
2012	0.0072	1.86	0.92	0.0033	1.30	0.94			
Ave.	0.0137	1.82	0.93	0.0071	1.40	0.93	0.0057	1.23	0.94

Table 9. The errors of the results of Case 2 by PTM, Ochiai, Sarobestu Mire

Year	Site D			Site M			Site U		
	CHI	AE	r	CHI	AE	r	CHI	AE	r
1983	0.0035	1.19	0.87	0.0031	1.04	0.84			
1984	0.0038	1.12	0.92				0.0104	1.83	0.87
1985	0.0143	2.36	0.79	0.0042	1.15	0.92	0.0010	0.60	0.95
1986	0.0244	2.78	0.94	0.0047	1.22	0.96	0.0246	2.77	0.93
1987	0.0064	1.62	0.92	0.0051	1.38	0.92	0.0045	1.17	0.94
1988	0.0103	2.13	0.96	0.0087	1.67	0.94	0.0104	1.91	0.93
1989	0.0231	2.89	0.96	0.0067	1.56	0.97	0.0053	1.35	0.98
1990	0.0185	2.14	0.95	0.0029	0.84	0.95	0.0015	0.65	0.97

1991	0.0303	2.81	0.85	0.0013	0.66	0.97	0.0060	1.45	0.90
1992	0.0119	2.10	0.91	0.0083	1.66	0.89	0.0034	1.11	0.95
1993	0.0178	2.46	0.96	0.0397	2.84	0.88	0.0422	3.19	0.86
1994	0.0200	2.45	0.92	0.0123	2.12	0.91	0.0068	1.68	0.93
1995	0.0092	1.62	0.97	0.0067	1.57	0.97	0.0024	0.87	0.97
1996	0.0232	2.59	0.70	0.0098	1.77	0.66	0.0132	2.03	0.54
1997	0.0132	1.94	0.98	0.0059	1.33	0.97	0.0071	1.49	0.89
1999	0.0182	1.99	0.94	0.0056	1.06	0.94	0.0083	1.40	0.89
2000	0.0074	1.47	0.95	0.0052	1.24	0.90	0.0055	1.19	0.90
2001	0.0088	1.48	0.95	0.0039	1.04	0.89	0.0024	0.86	0.89
2002	0.0037	1.10	0.97	0.0026	0.85	0.94	0.0015	0.57	0.95
2003	0.0188	2.44	0.94	0.0126	1.87	0.83	0.0066	1.26	0.89
2004	0.0142	2.15	0.95	0.0060	1.50	0.93	0.0017	0.71	0.96
2005	0.0150	2.08	0.95	0.0168	2.11	0.86	0.0048	1.35	0.95
2006	0.0146	2.13	0.91	0.0064	1.51	0.90			
2007	0.0034	1.26	0.98	0.0036	1.33	0.98			
2008	0.0152	2.71	0.86	0.0152	2.82	0.83			
2009	0.0031	1.22	0.94	0.0050	1.59	0.87			
2010	0.0118	2.26	0.97	0.0027	1.00	0.98			
2011	0.0102	2.43	0.95	0.0024	1.08	0.98			
2012	0.0148	2.65	0.90	0.0055	1.72	0.91			
Ave.	0.0134	2.05	0.92	0.0076	1.48	0.91	0.0081	1.40	0.91

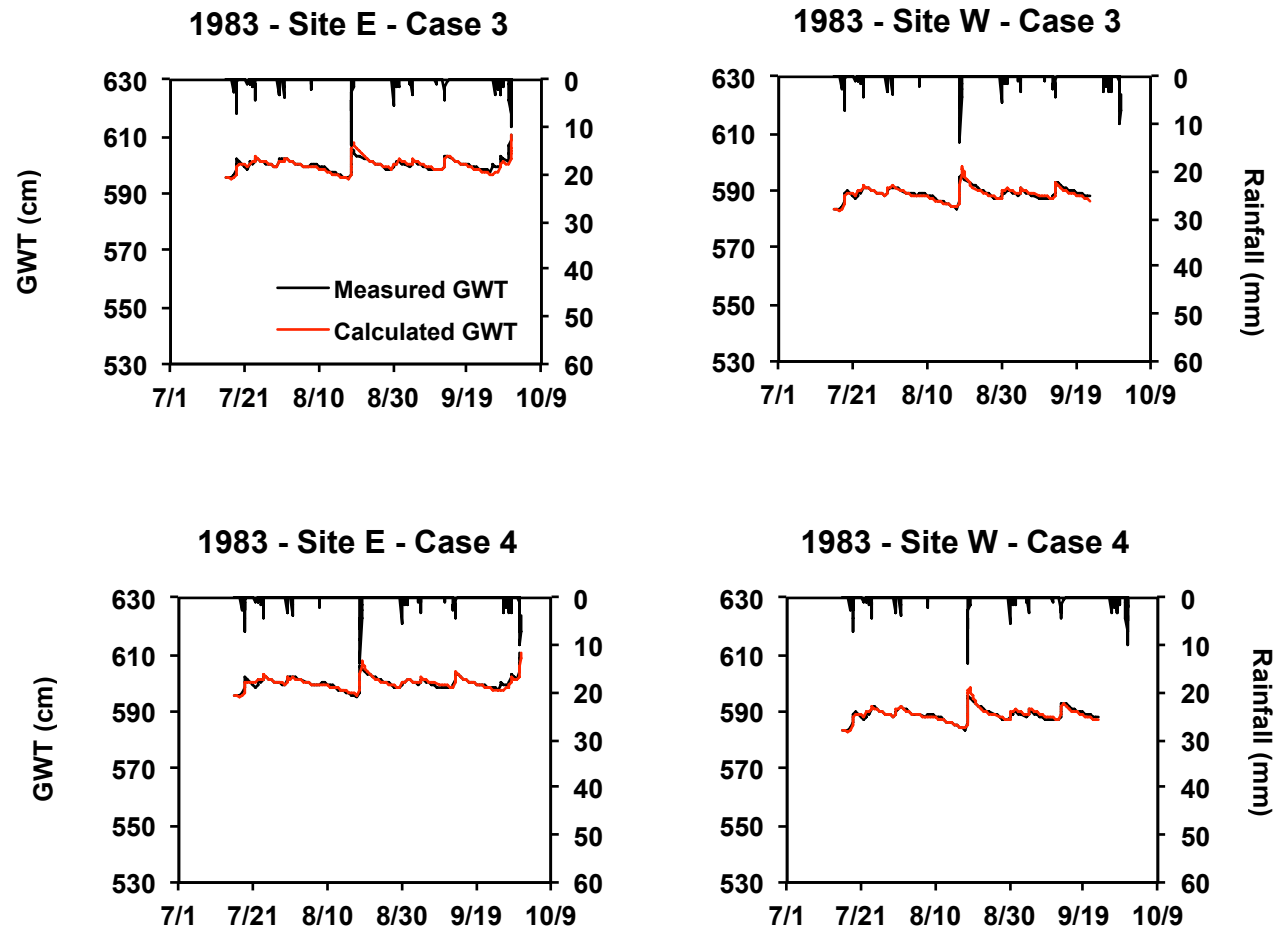
Table 10. The errors of the optimum results by modified PTM, Genseikaen, Sarobestu Mire

Year	Site E			Site W			Site WB		
	CHI	AE	r	CHI	AE	r	CHI	AE	r
1983	0.0006	0.40	0.95	0.0005	0.38	0.98			
1984	0.0014	0.67	0.97	0.0016	0.71	0.98			
1985	0.0011	0.59	0.95						
1987	0.0012	0.64	0.94	0.0011	0.65	0.90			
1988	0.0031	1.08	0.98						

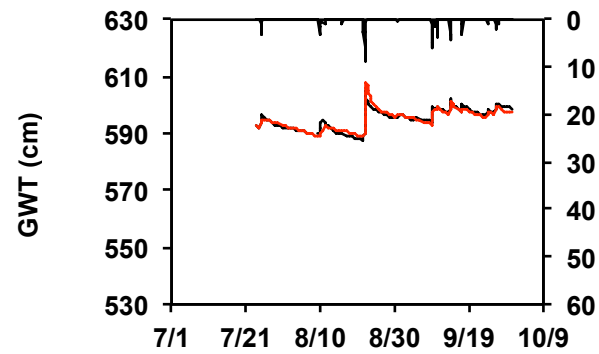
1989	0.0053	1.22	0.95						
1991	0.0009	0.45	0.95	0.0007	0.51	0.98	0.0033	1.09	0.98
1992	0.0041	1.20	0.93	0.0006	0.41	0.98	0.0026	0.88	0.97
1993	0.0010	0.53	0.94	0.0006	0.43	0.98	0.0066	1.27	0.97
1994	0.0019	0.77	0.95	0.0012	0.65	0.98	0.0054	1.24	0.98
1995	0.0022	0.89	0.95	0.0008	0.50	0.98	0.0043	1.17	0.95
1996	0.0036	1.28	0.90	0.0005	0.41	0.96	0.0025	0.96	0.95
1997	0.0015	0.73	0.97	0.0009	0.57	0.97	0.0074	1.57	0.96
1998	0.0036	1.17	0.94	0.0018	0.81	0.96	0.0065	1.50	0.97
1999	0.0018	0.74	0.98	0.0008	0.50	0.96	0.0079	1.60	0.95
2000	0.0013	0.67	0.94	0.0009	0.55	0.96	0.0036	1.08	0.97
2001	0.0015	0.68	0.96	0.0008	0.46	0.96	0.0030	0.89	0.96
2002	0.0005	0.47	0.97	0.0004	0.39	0.98	0.0017	0.71	0.99
2003	0.0008	0.52	0.97				0.0114	2.19	0.98
2004	0.0008	0.57	0.98	0.0015	0.66	0.96			
2005	0.0028	0.95	0.96	0.0017	0.67	0.98			
2006	0.0008	0.47	0.98				0.0116	2.06	0.91
2007	0.0010	0.51	0.98	0.0016	0.72	0.98	0.0066	1.37	0.99
2008	0.0023	0.98	0.94	0.0015	0.71	0.96	0.0087	1.81	0.97
2009	0.0006	0.43	0.97	0.0008	0.48	0.94	0.0010	0.57	0.94
2010	0.0015	0.71	0.97	0.0017	0.75	0.97	0.0075	1.34	0.97
2011	0.0011	0.60	0.99	0.0021	0.70	0.97	0.0059	1.29	0.98
2012	0.0017	0.77	0.97	0.0020	0.88	0.95	0.0080	1.51	0.95
2013	0.0028	1.04	0.84	0.0009	0.54	0.94	0.0040	1.12	0.92
Ave.	0.0018	0.75	0.95	0.0011	0.58	0.97	0.0057	1.30	0.96

APPENDIX FIGURES

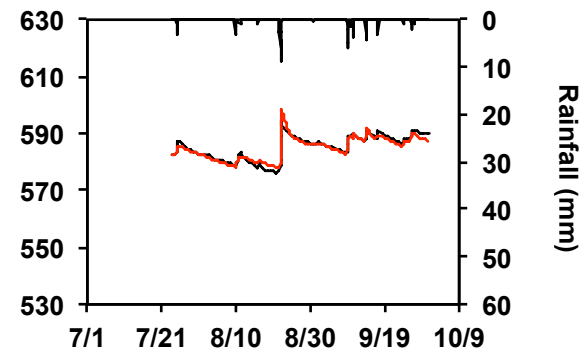
Figure 1. Simulation results of Gensekaen, Sarobestu Mire by PTM



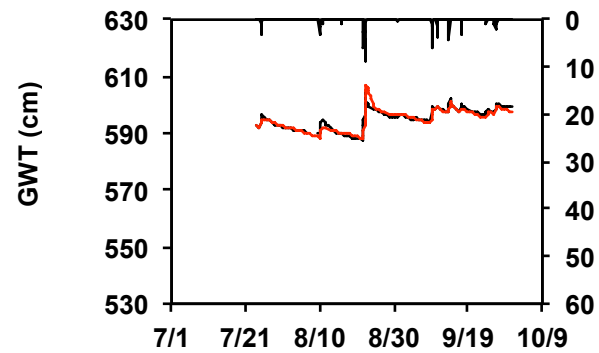
1984 - Site E - Case 3



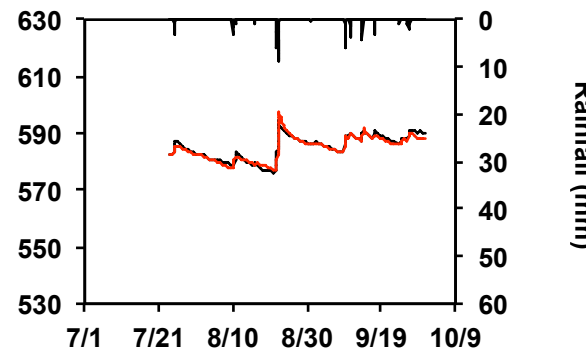
1984 - Site W - Case 3

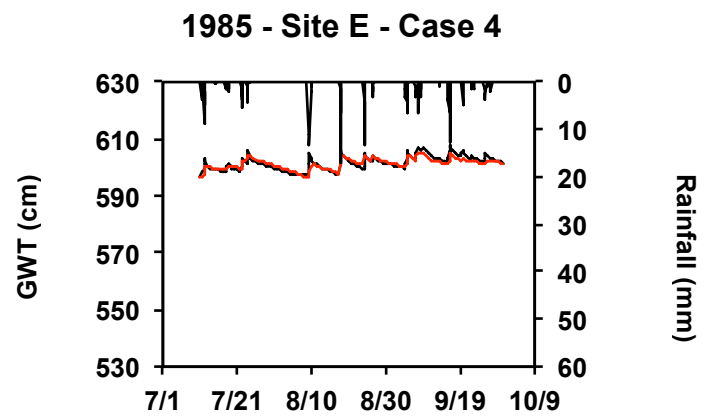
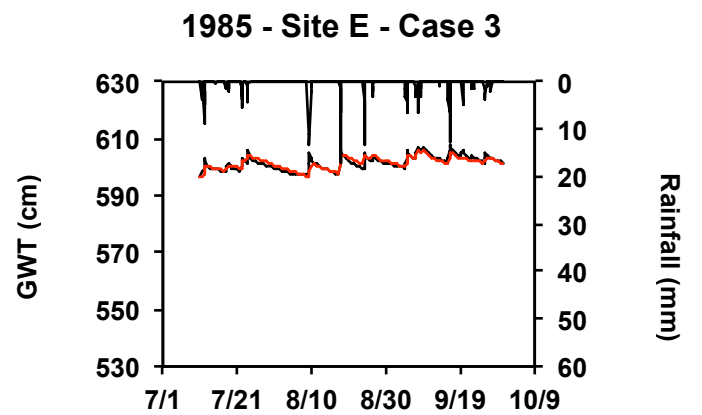


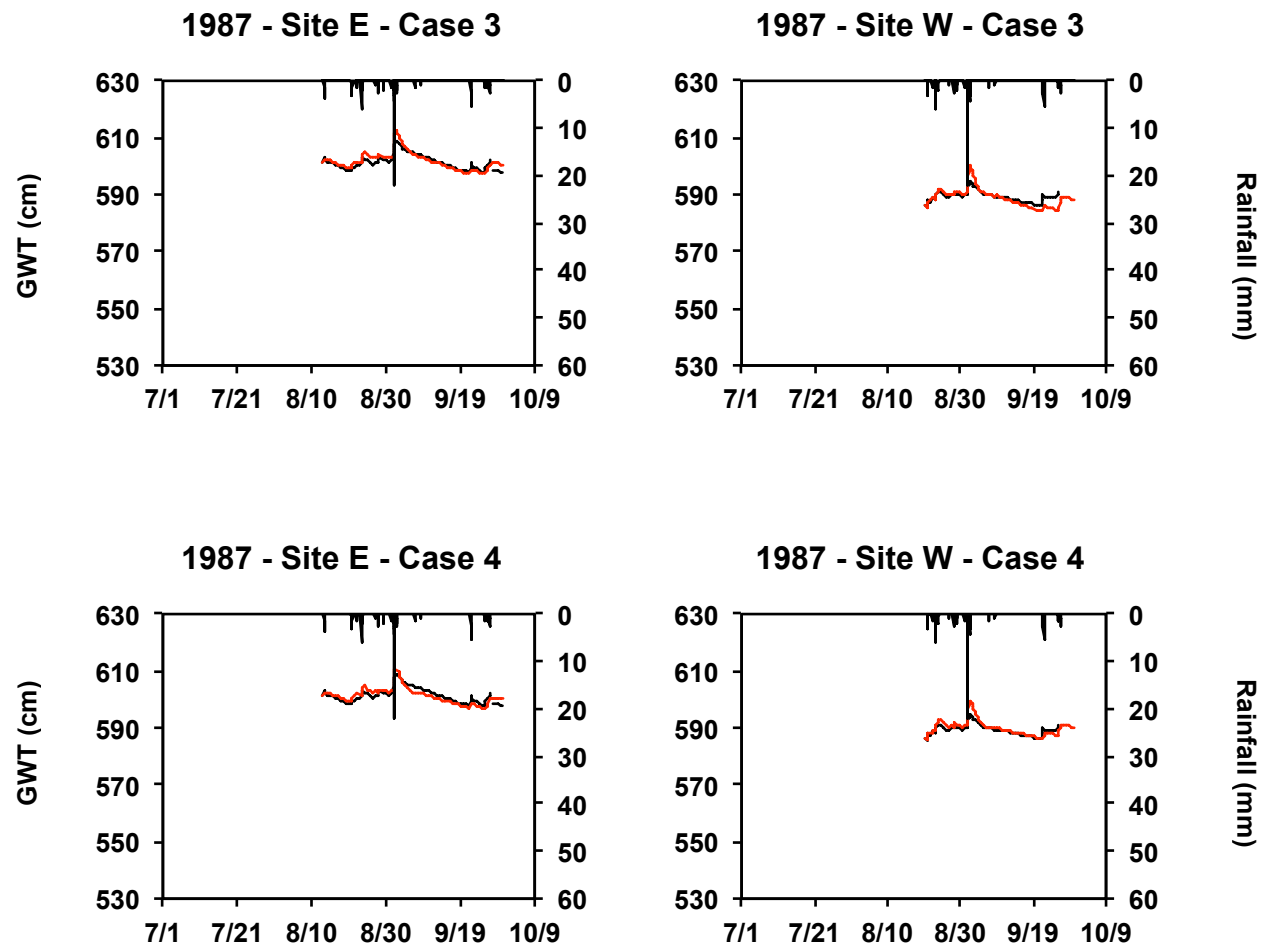
1984 - Site E - Case 4



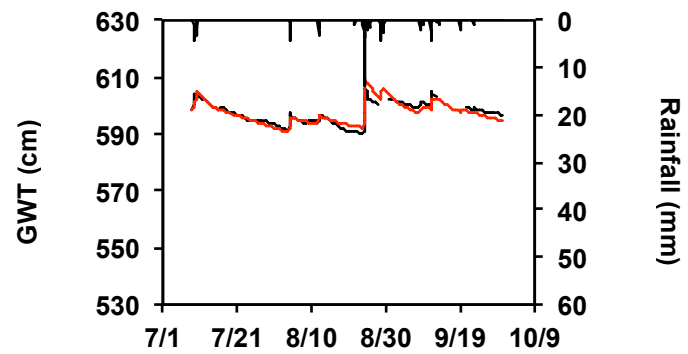
1984 - Site W - Case 4



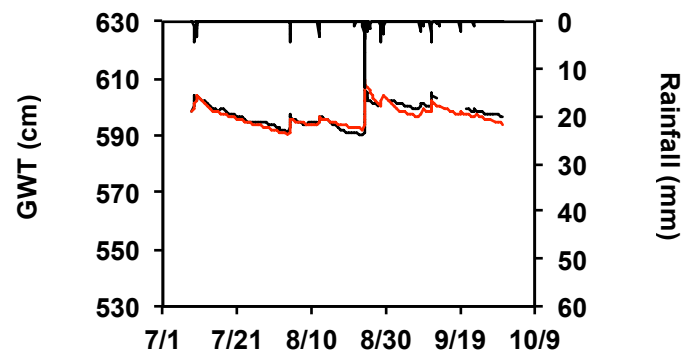




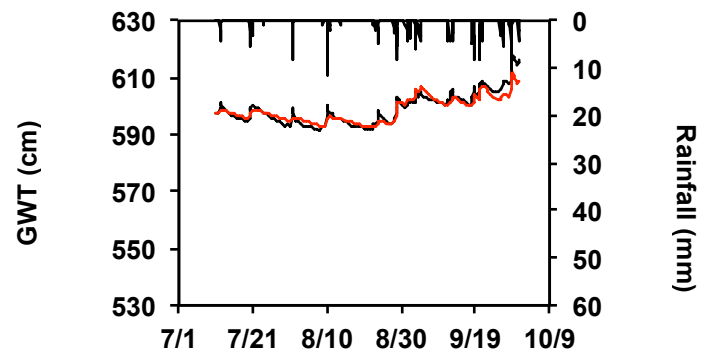
1988 - Site E - Case 3



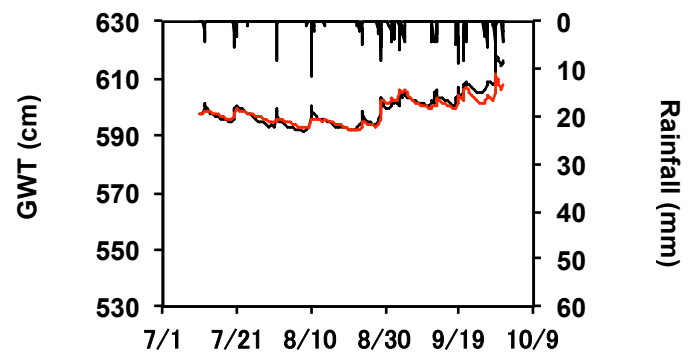
1988 - Site E - Case 4

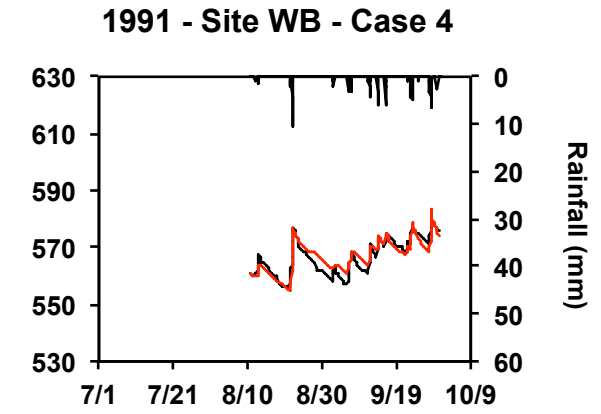
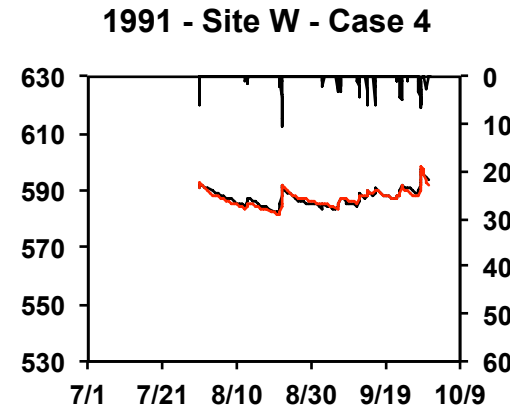
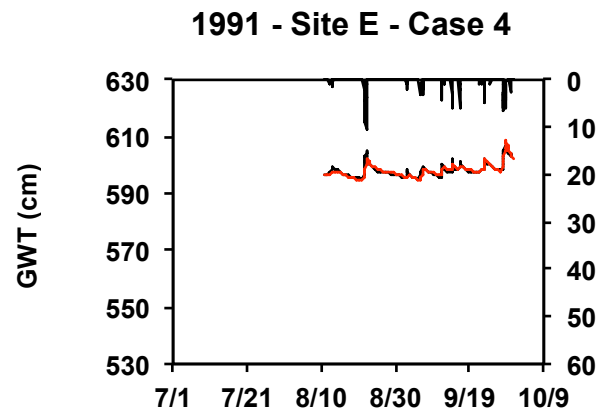
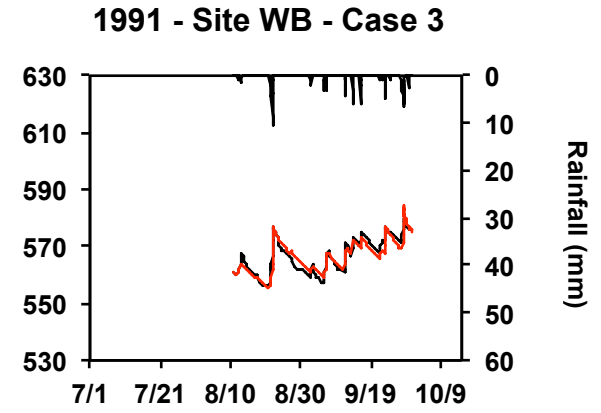
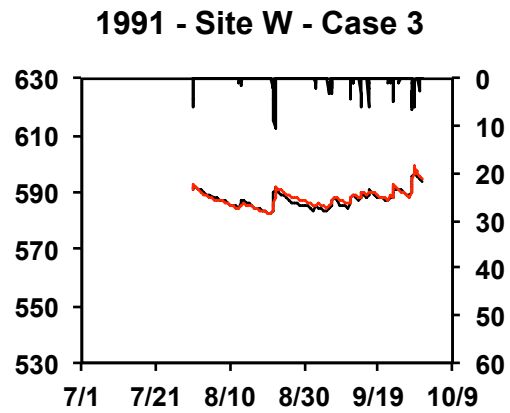
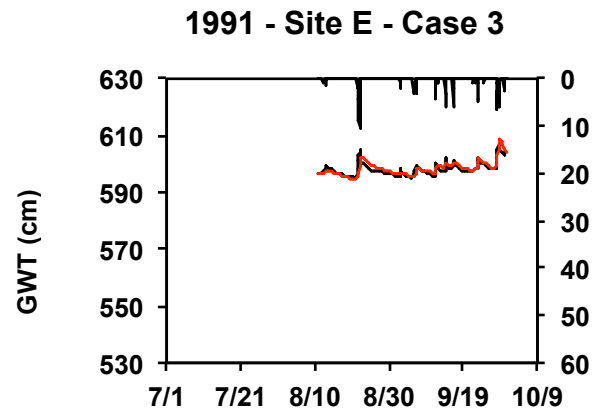


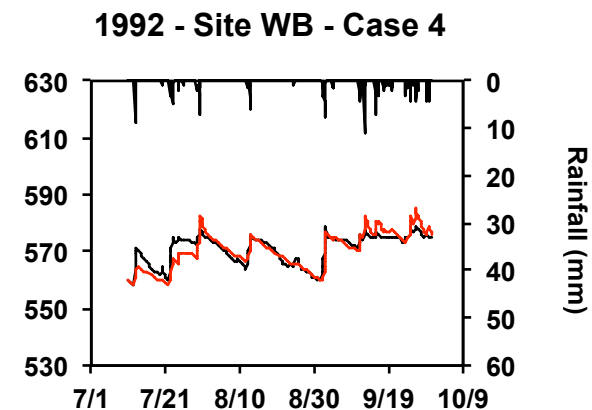
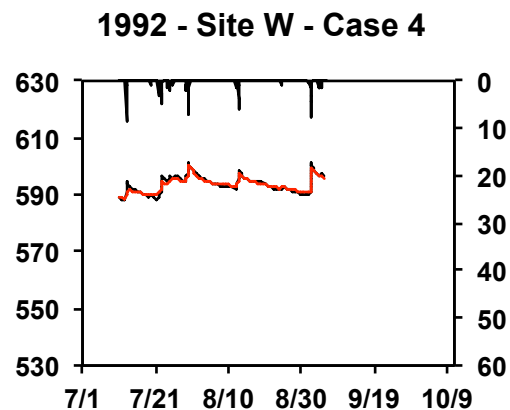
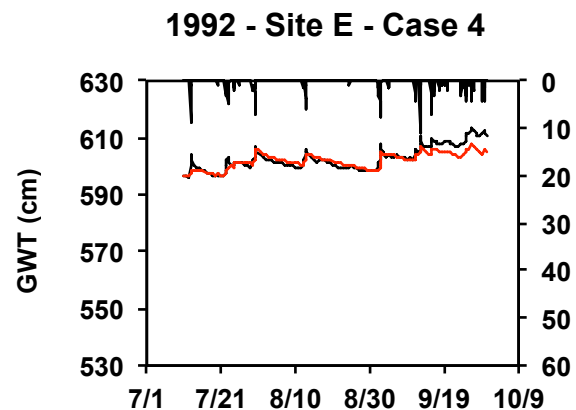
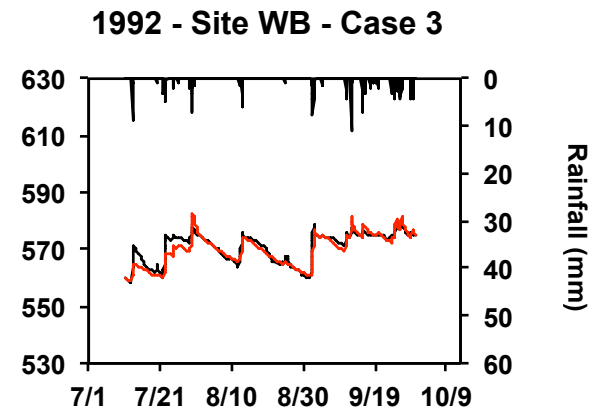
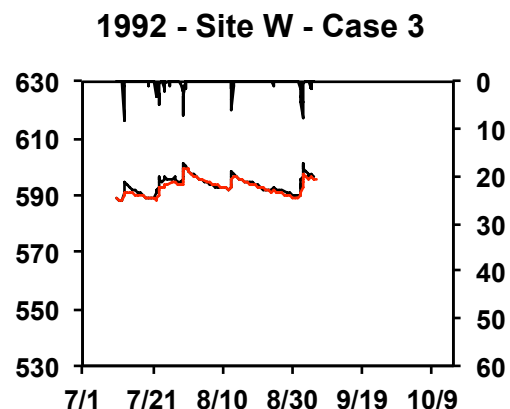
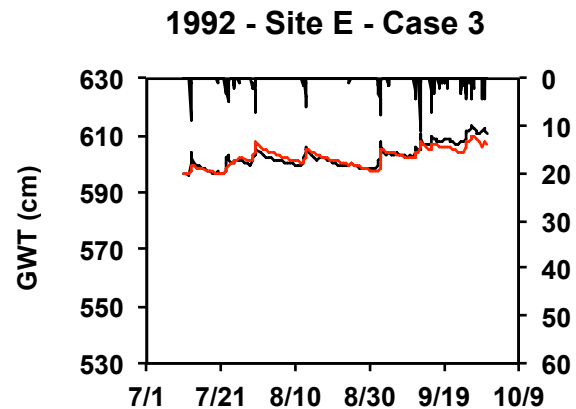
1989 - Site E - Case 3

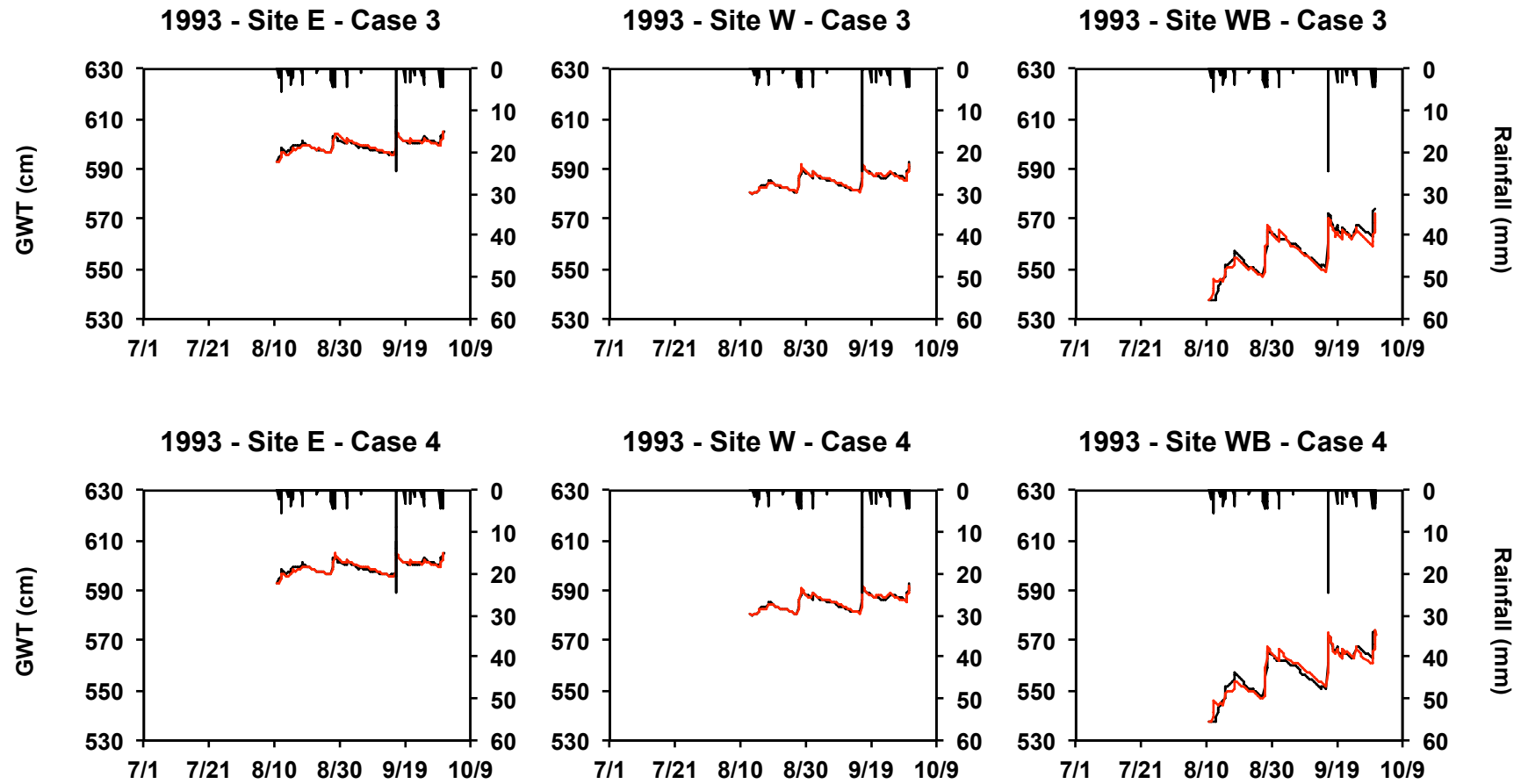


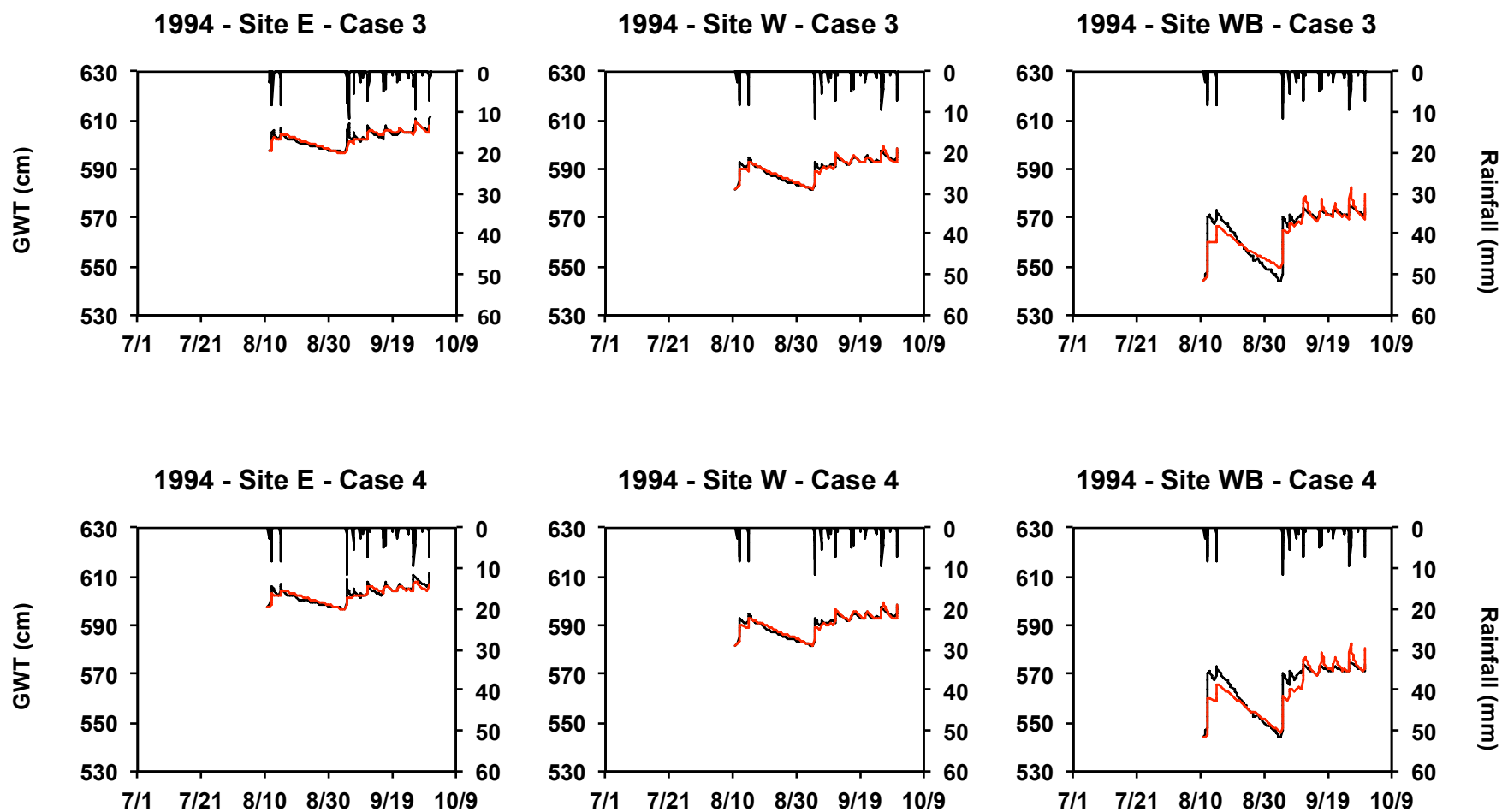
1989 - Site E - Case 4

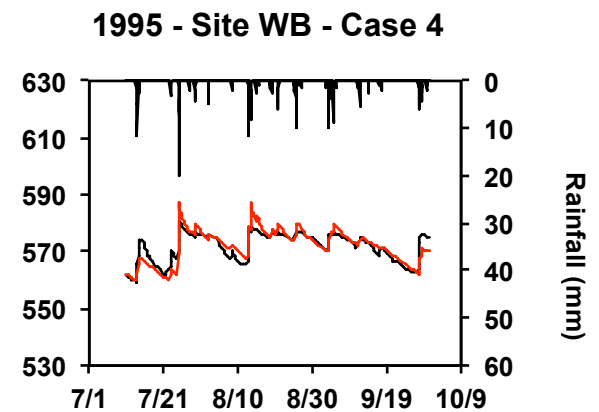
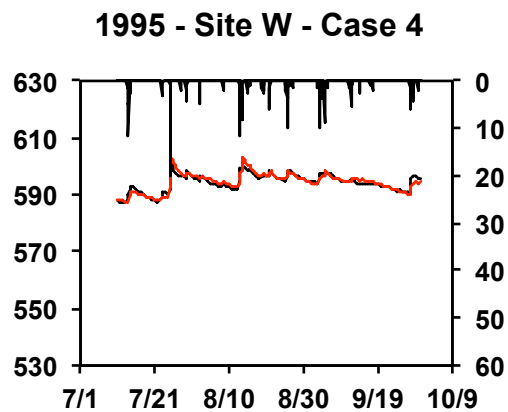
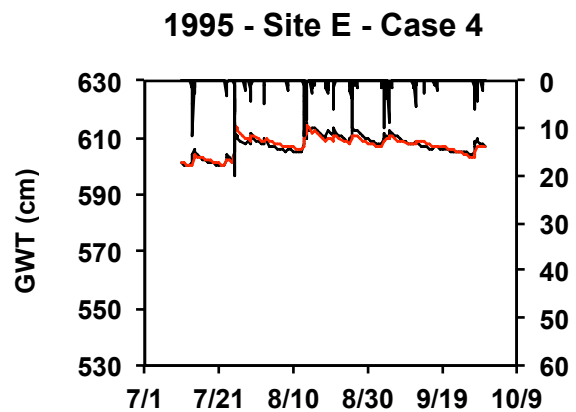
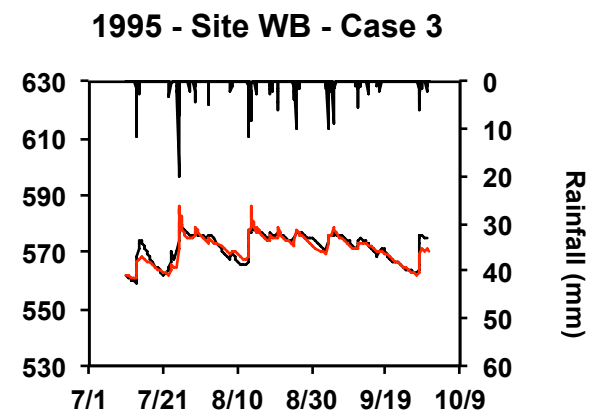
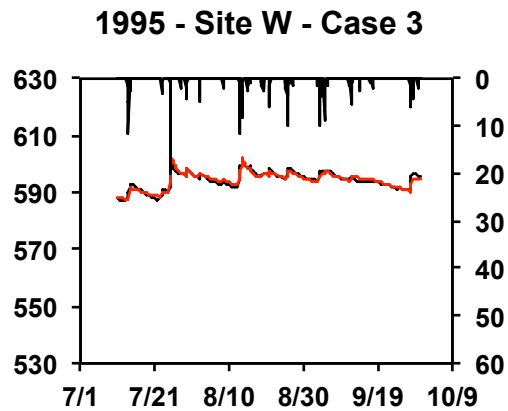
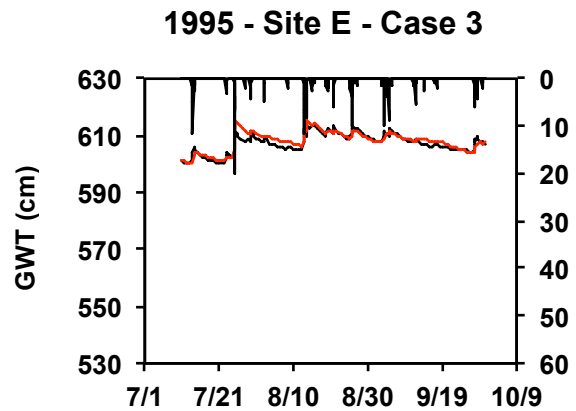


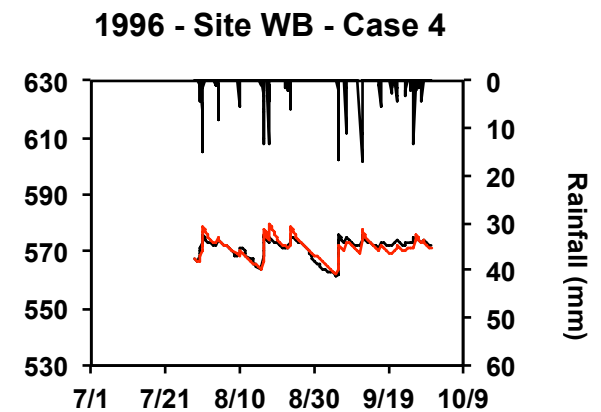
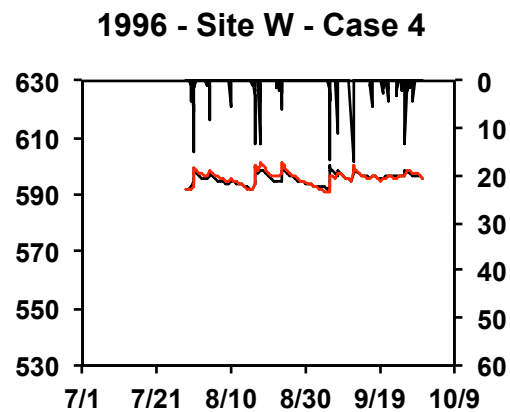
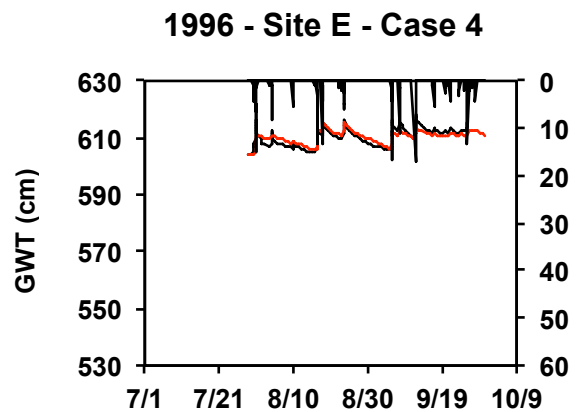
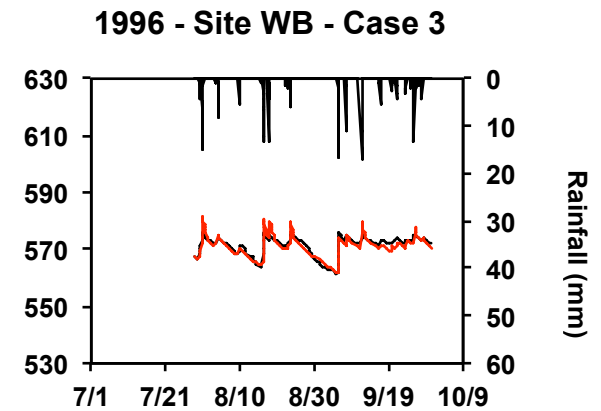
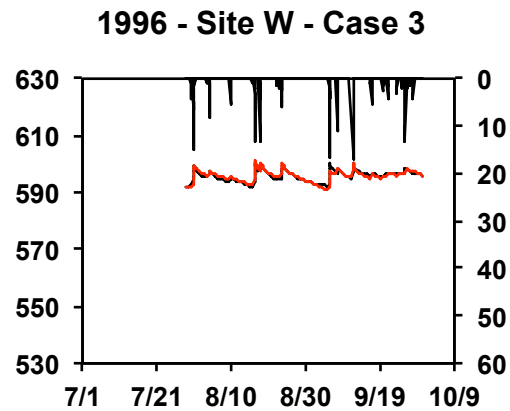
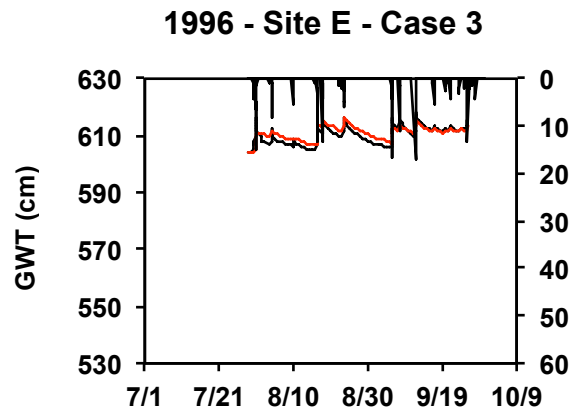


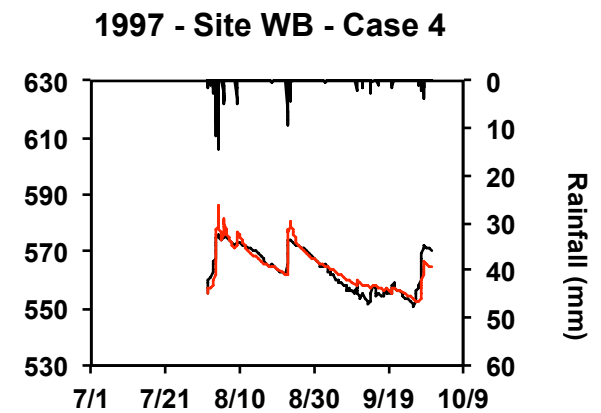
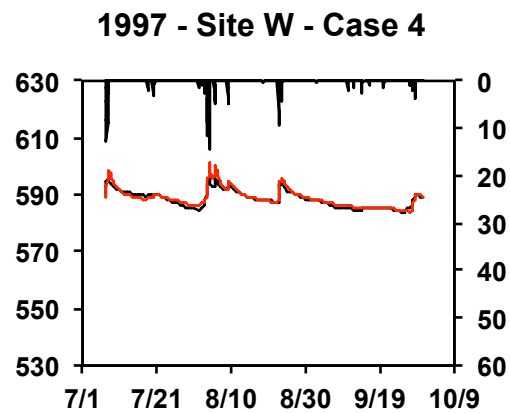
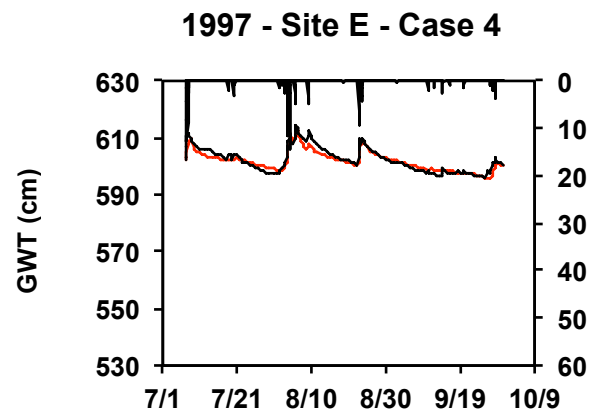
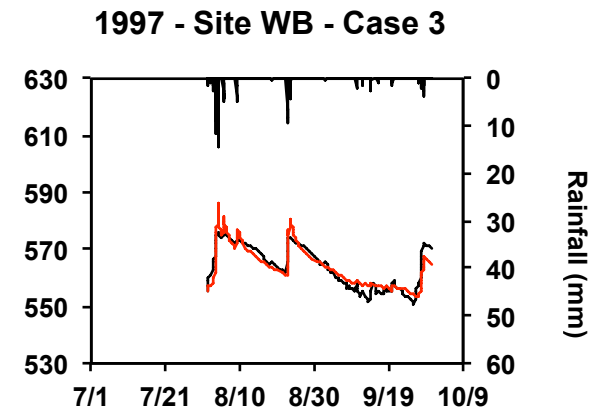
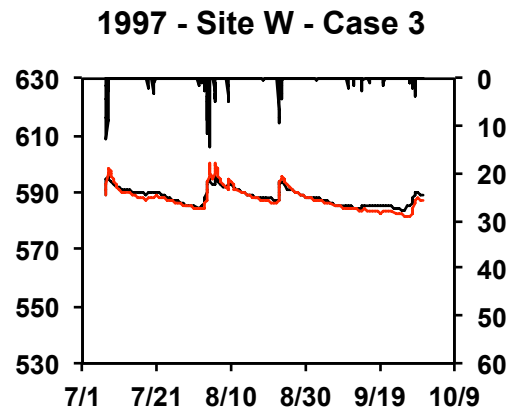
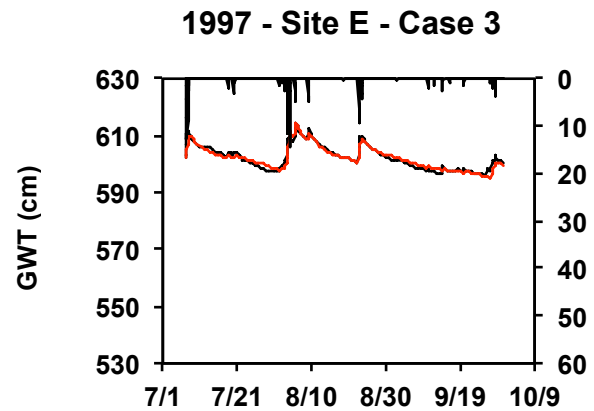


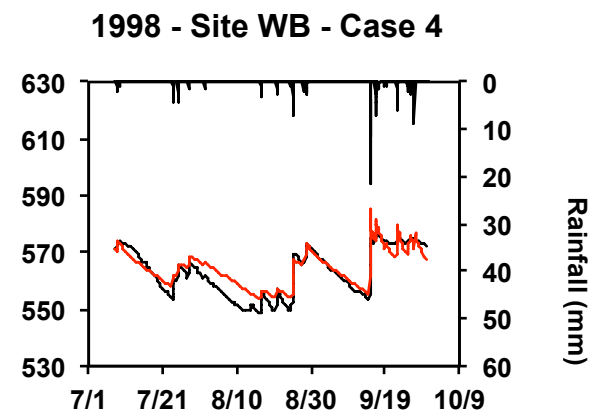
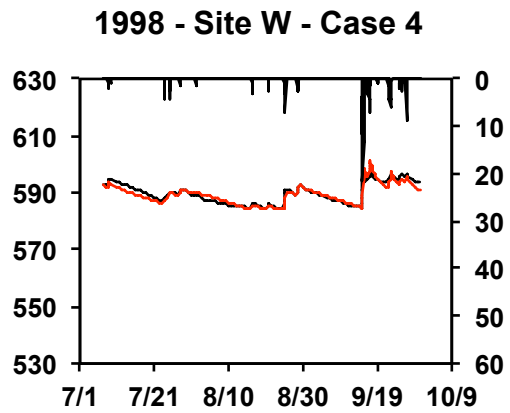
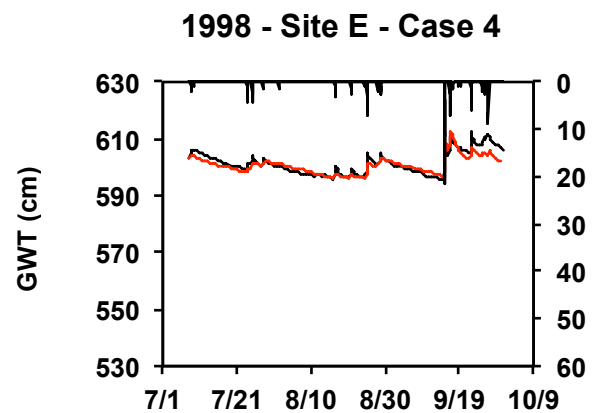
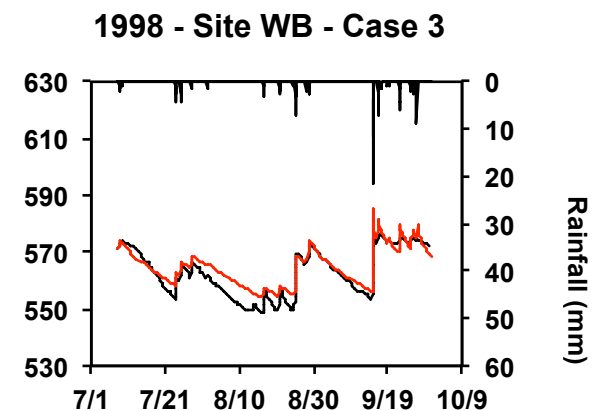
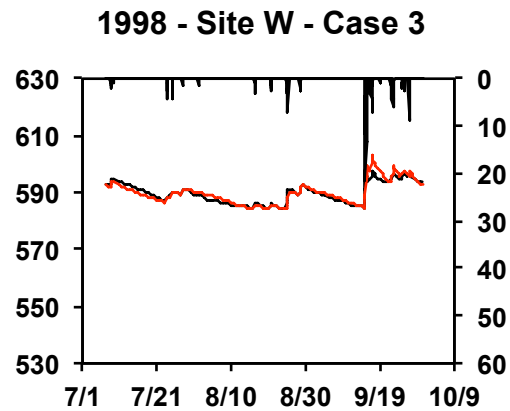
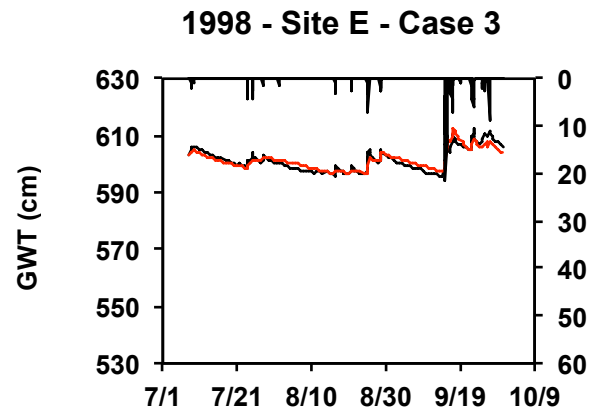


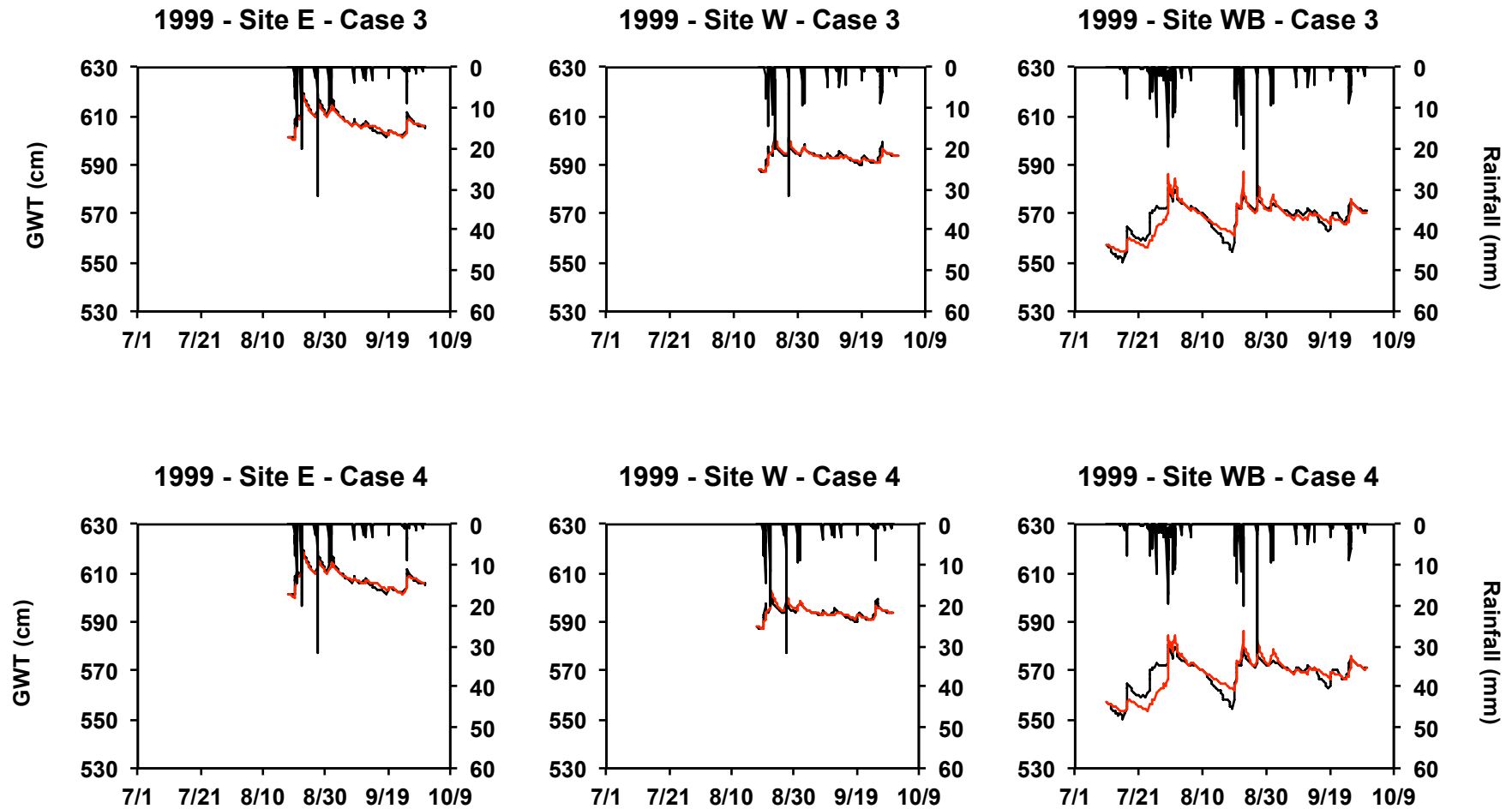


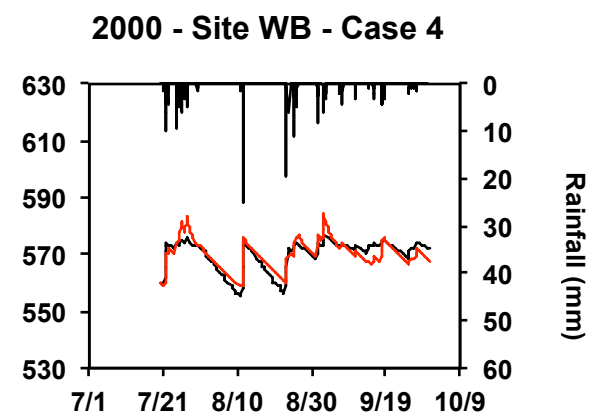
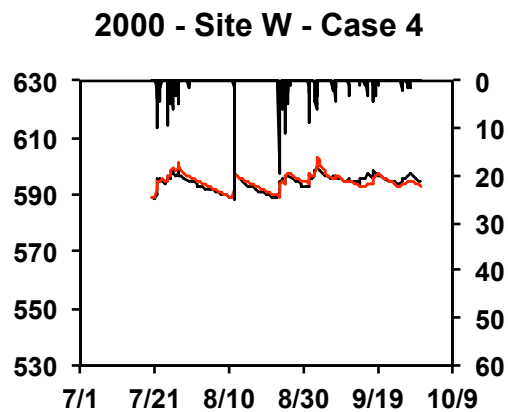
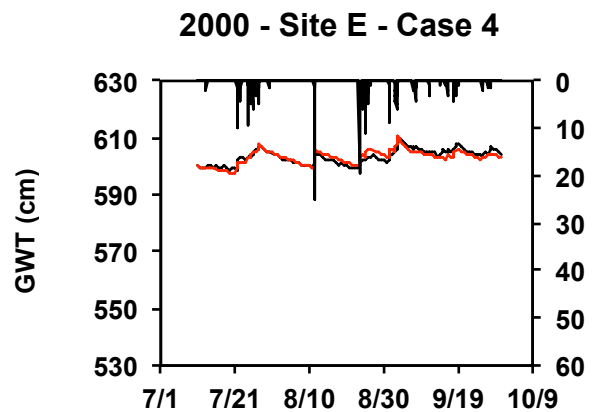
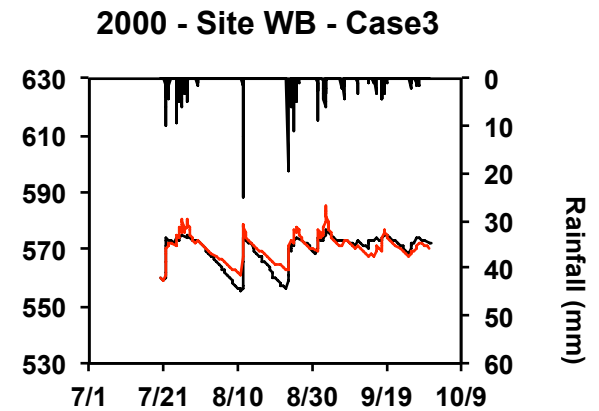
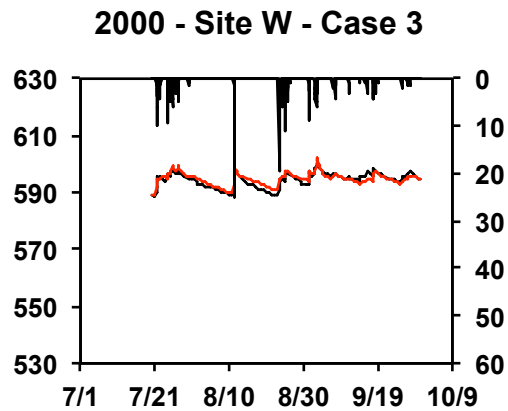
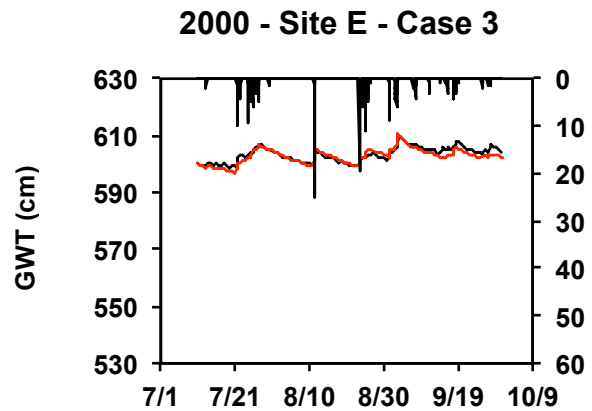


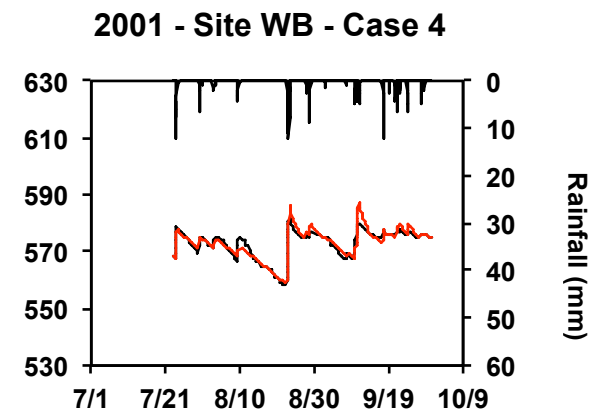
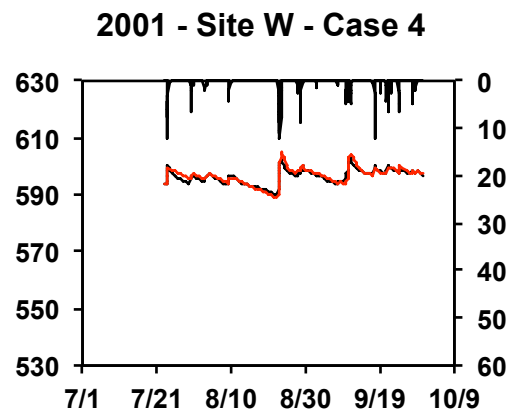
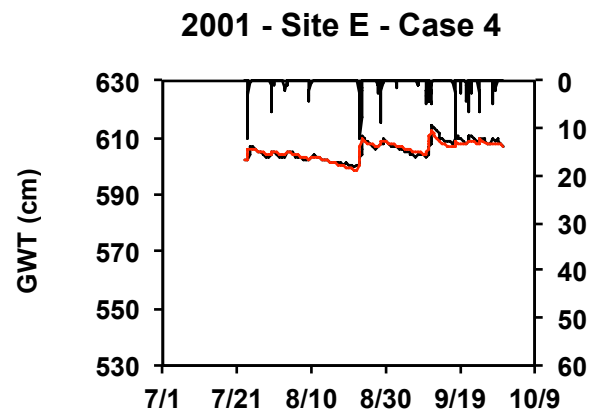
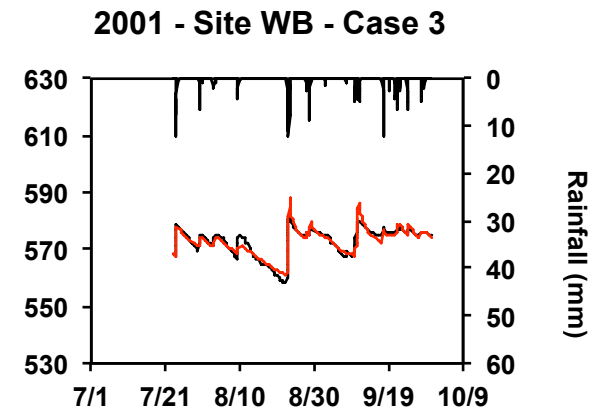
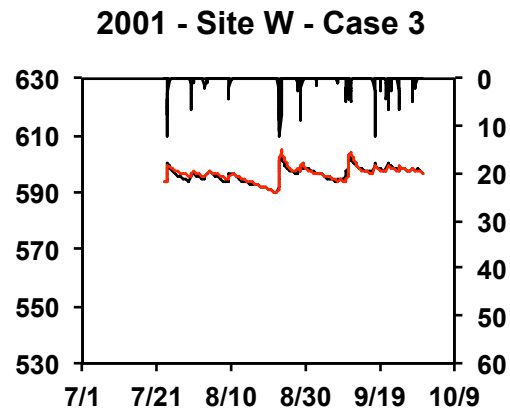
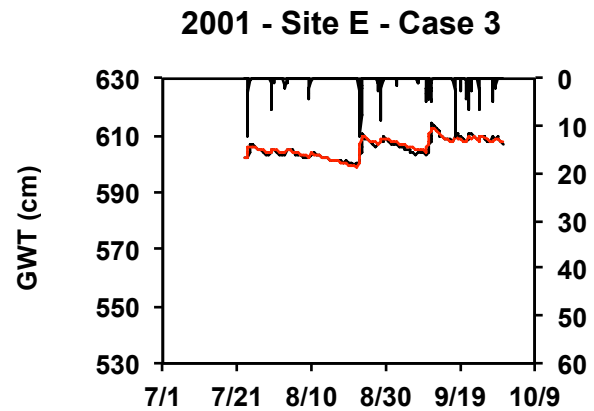


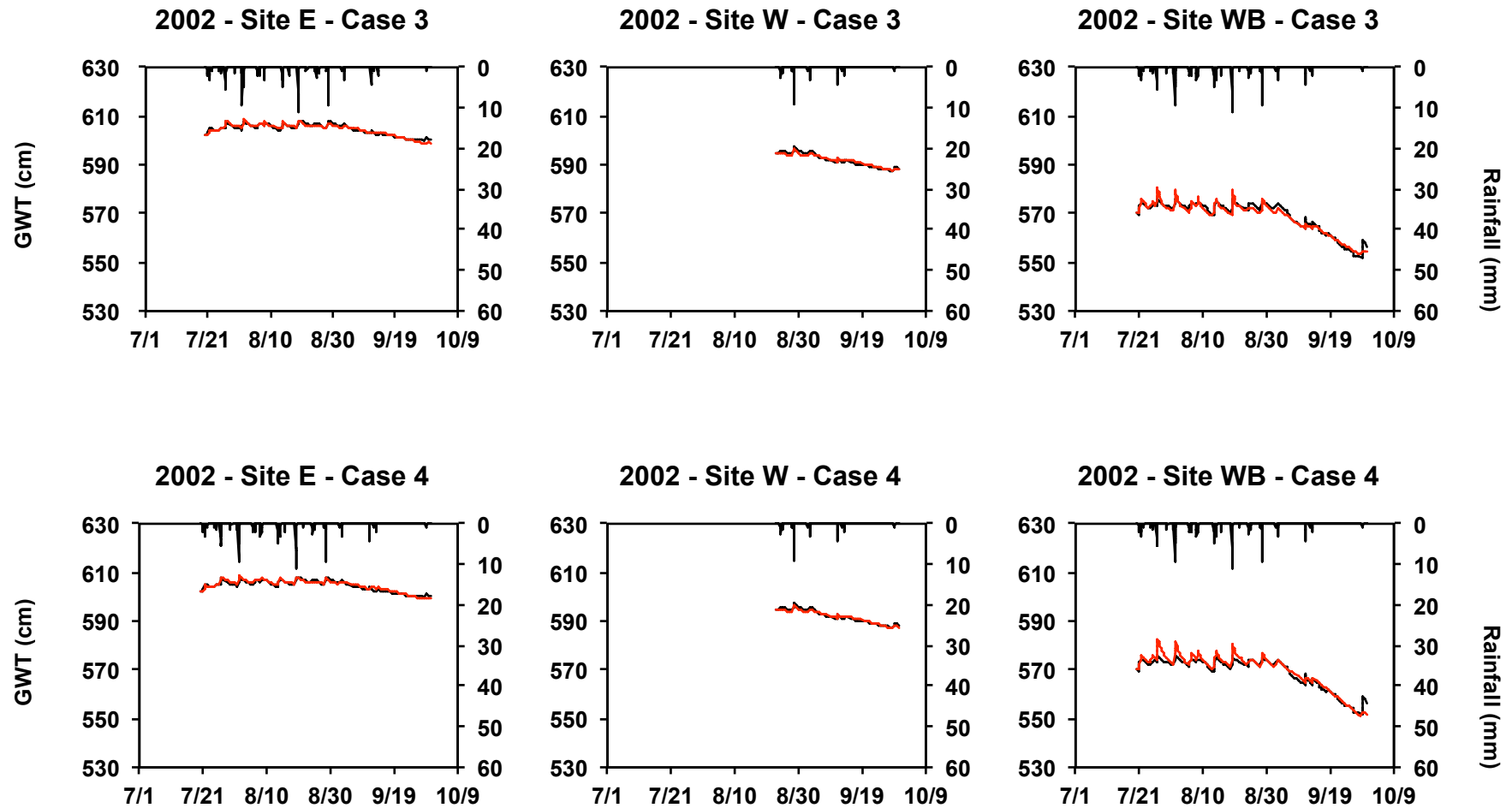


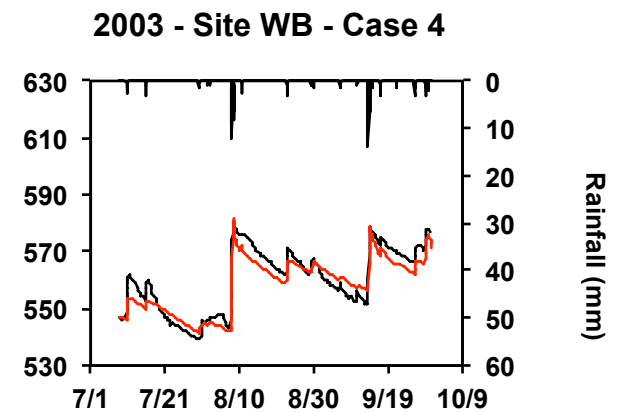
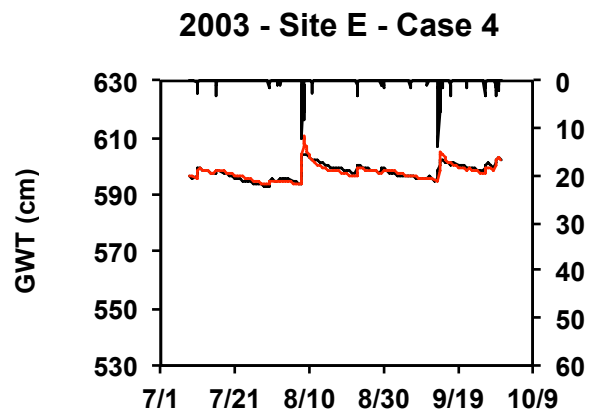
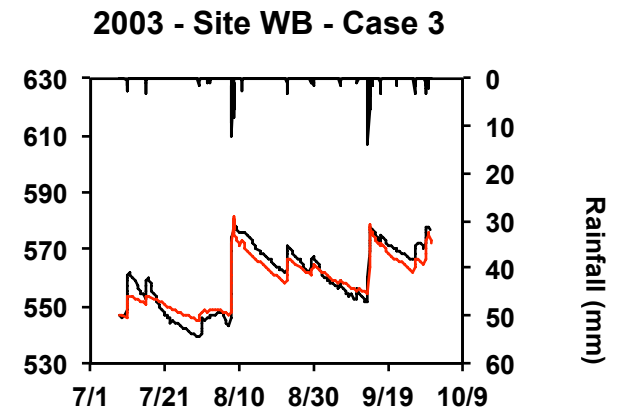
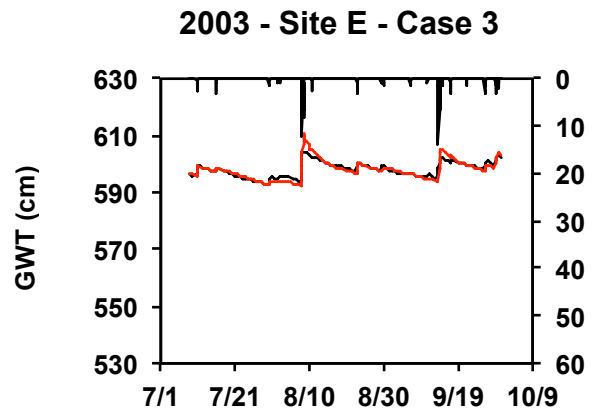


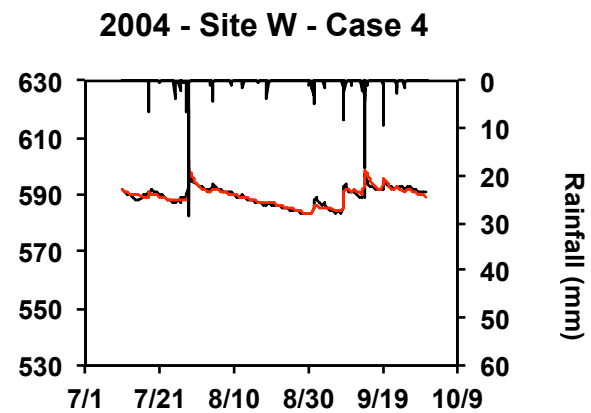
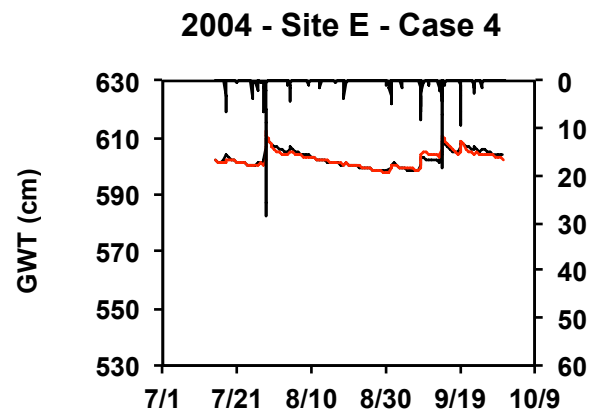
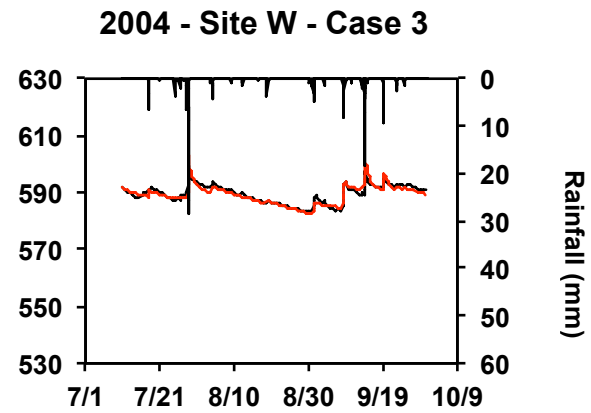
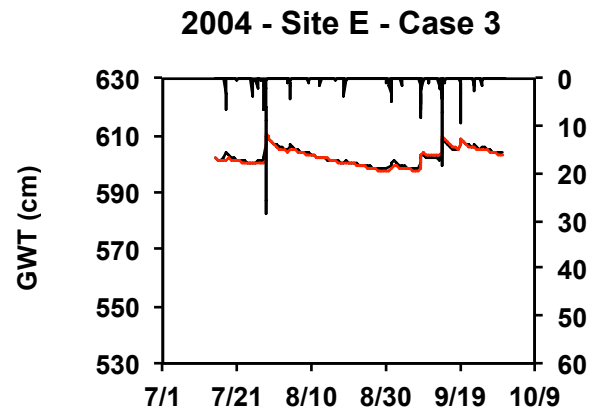


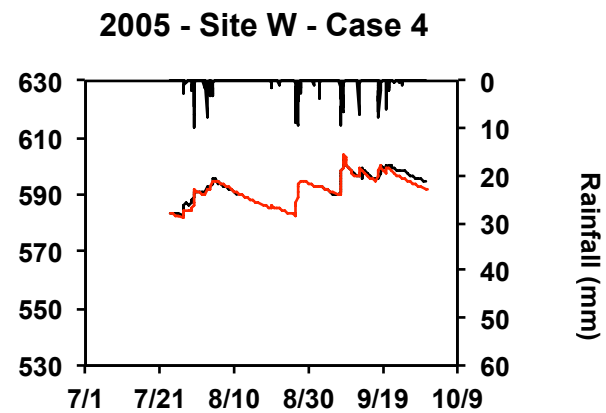
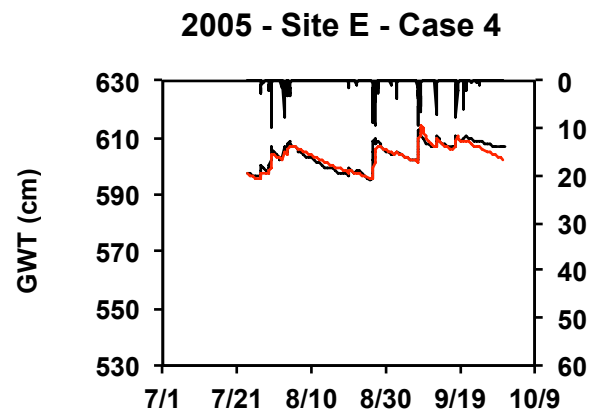
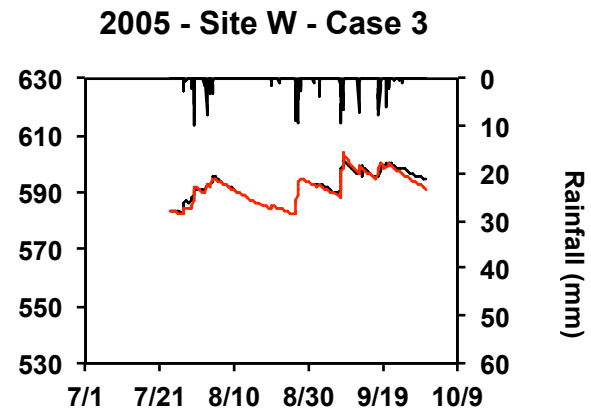
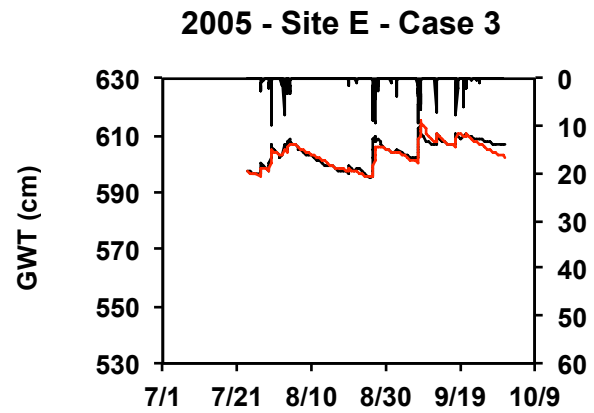


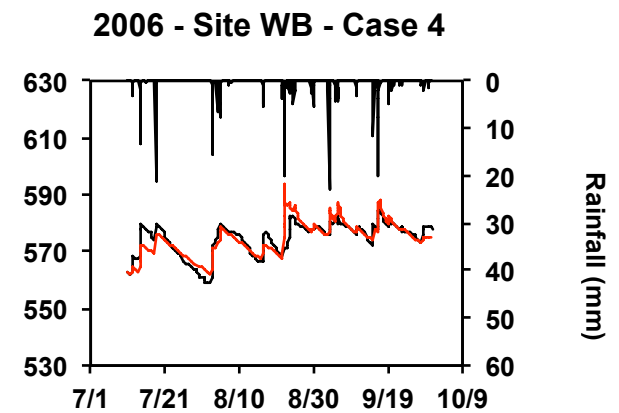
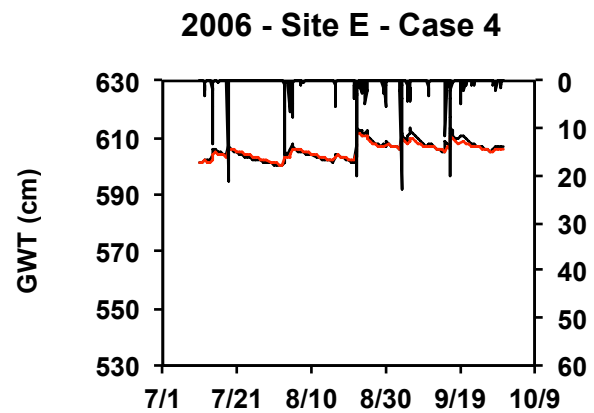
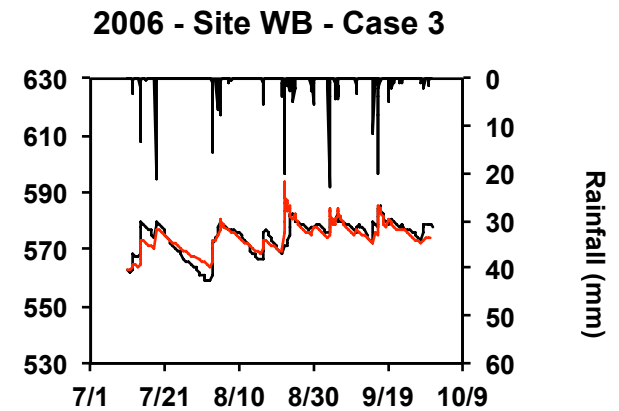
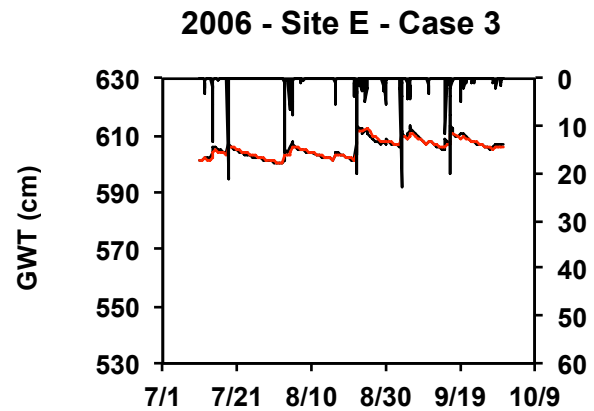


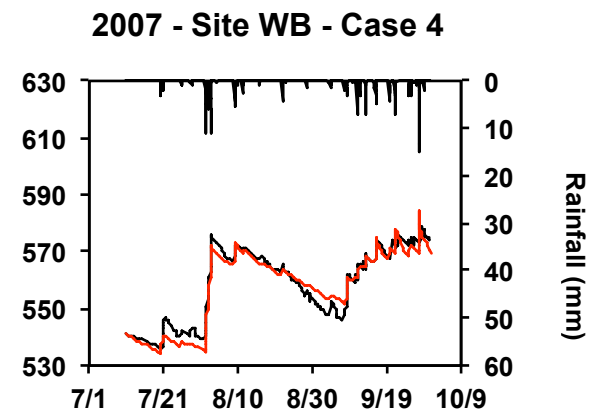
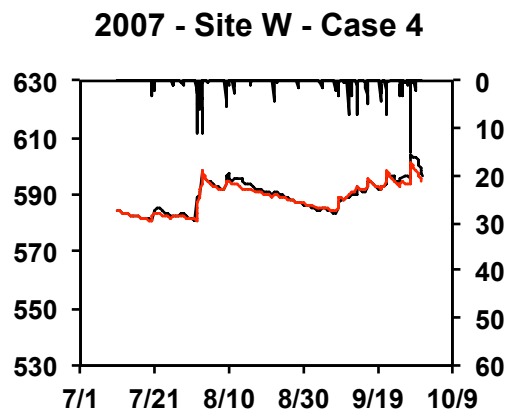
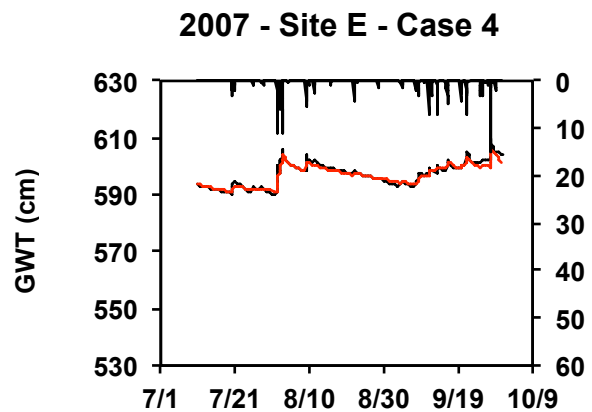
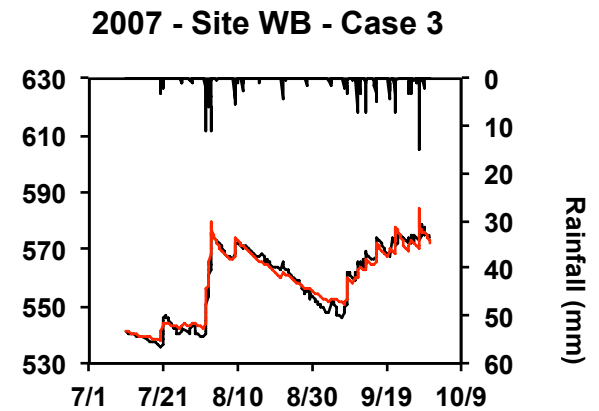
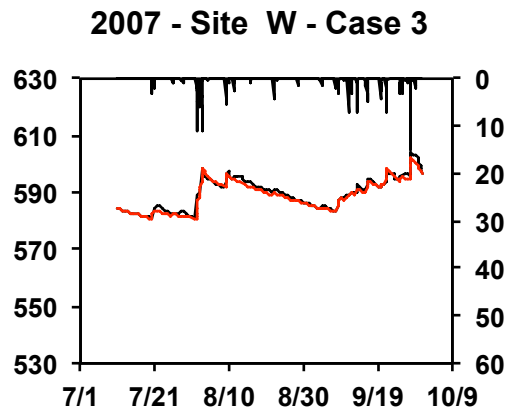
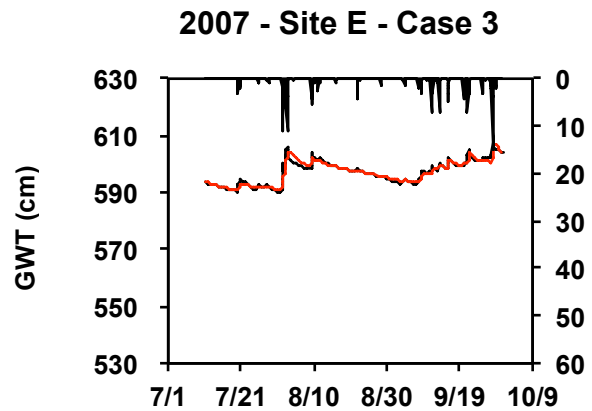


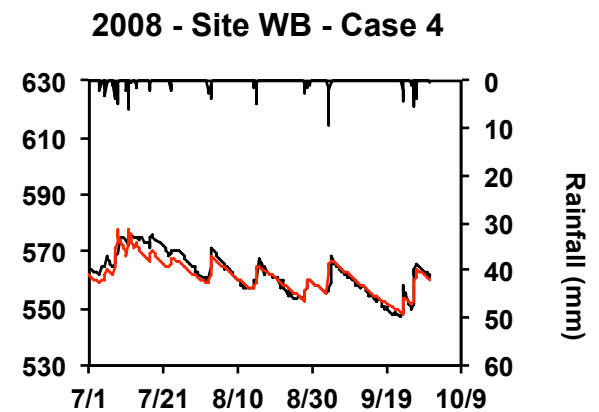
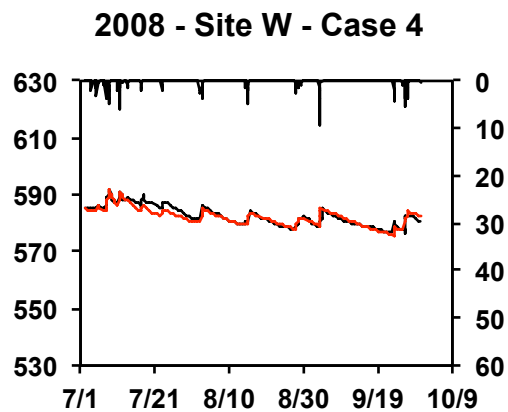
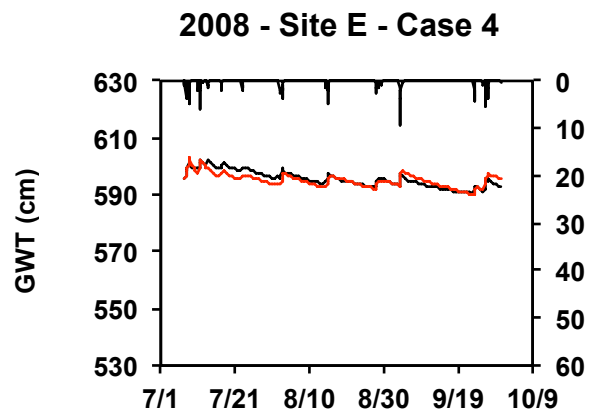
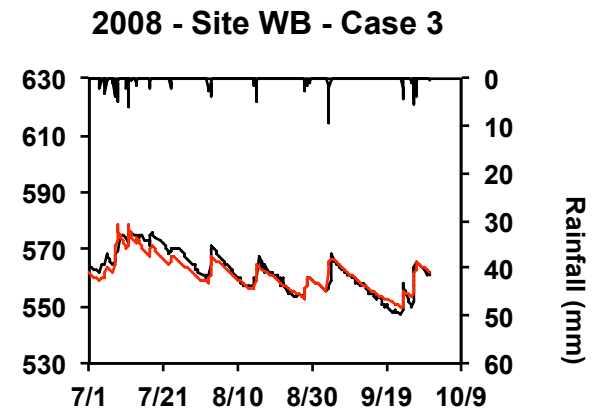
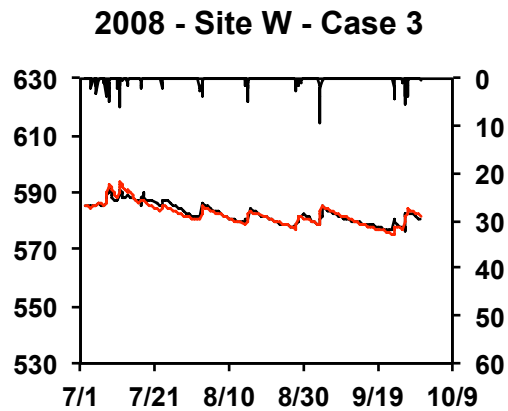
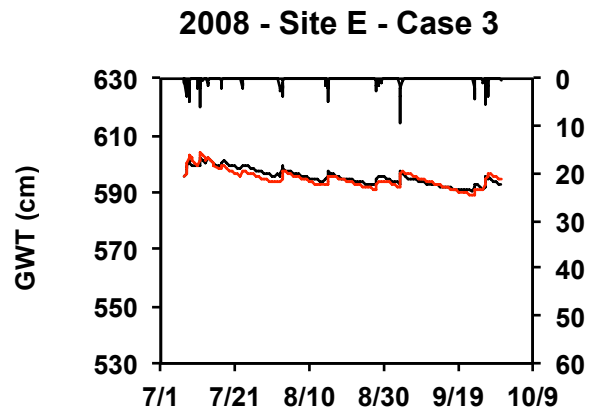


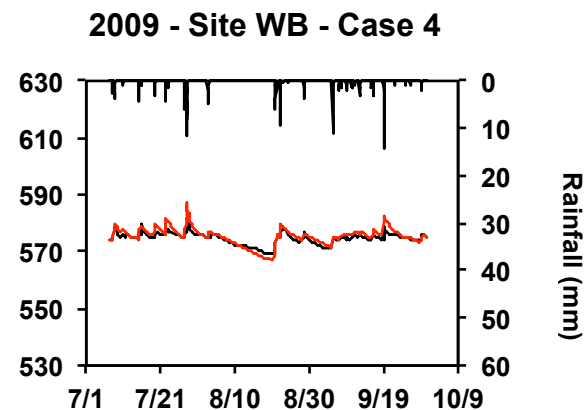
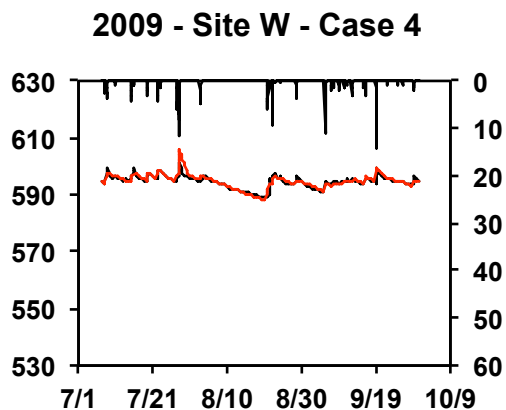
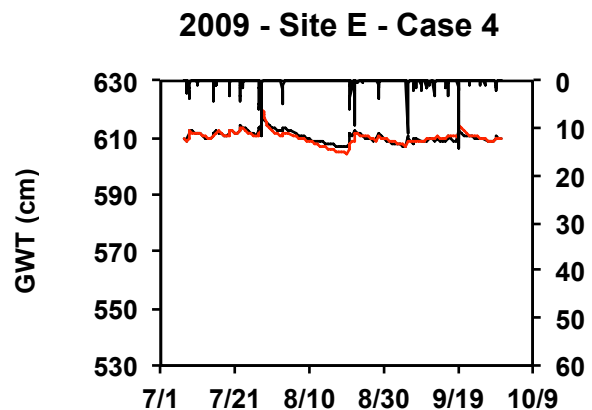
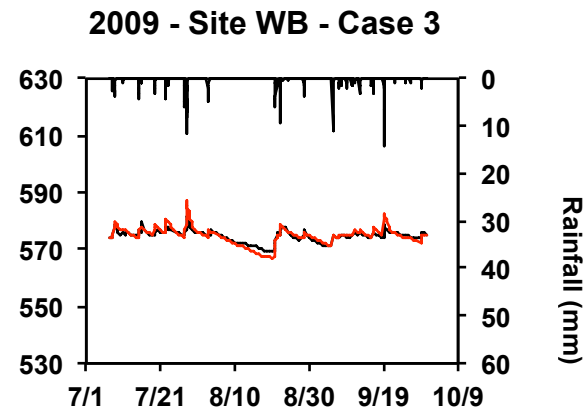
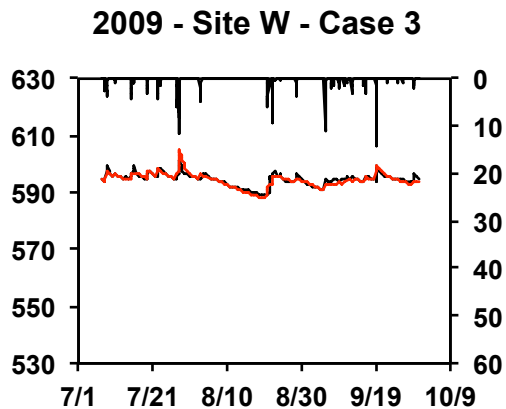
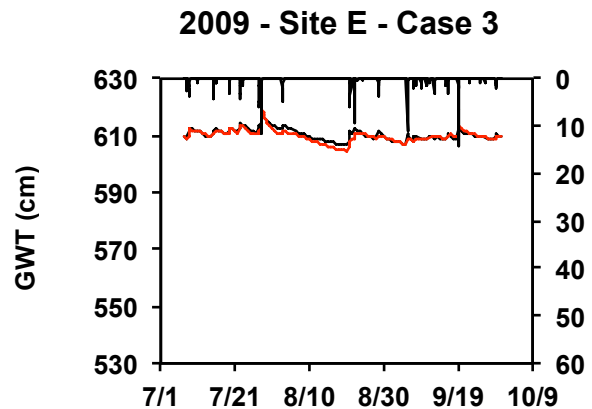


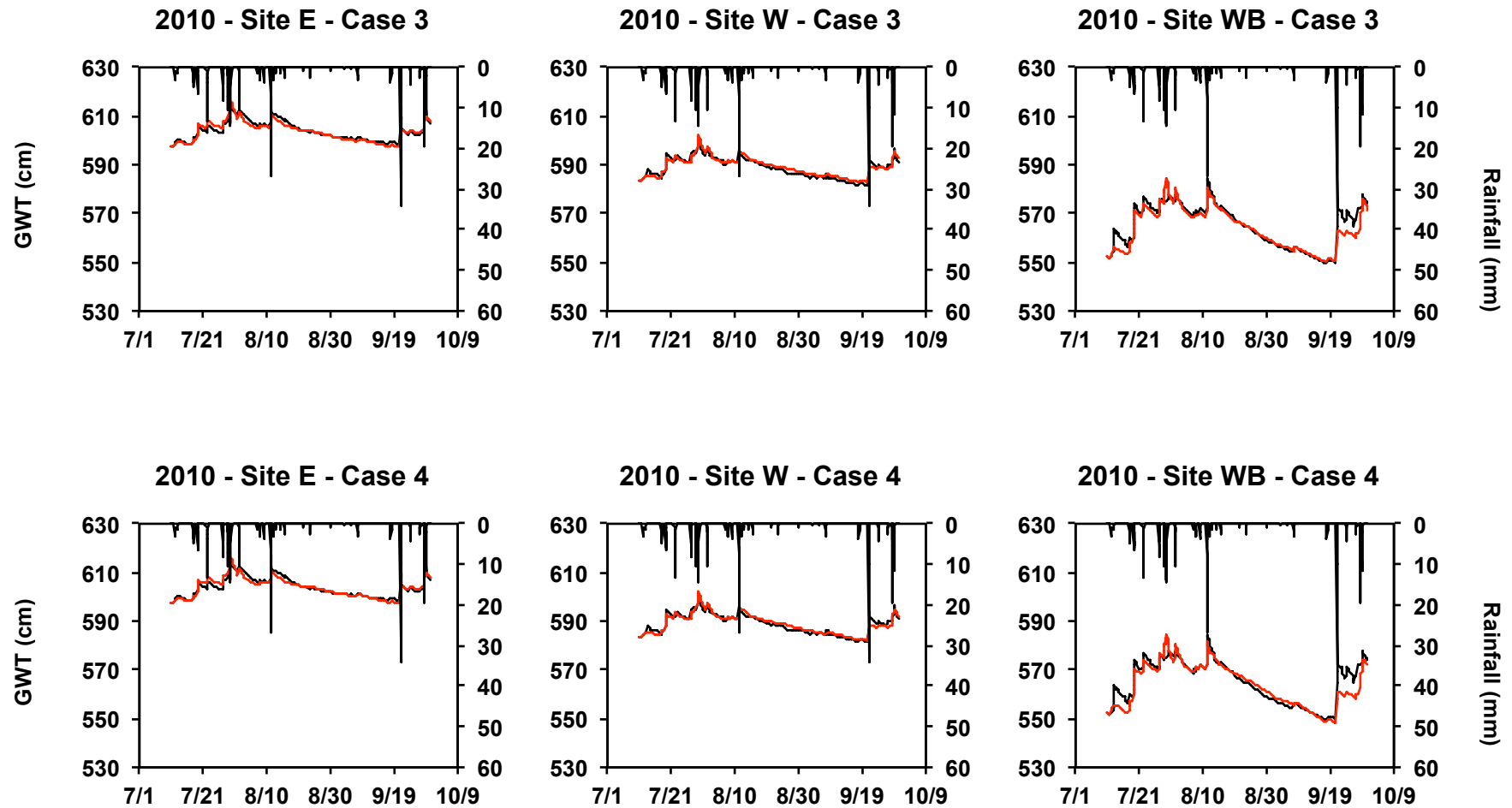


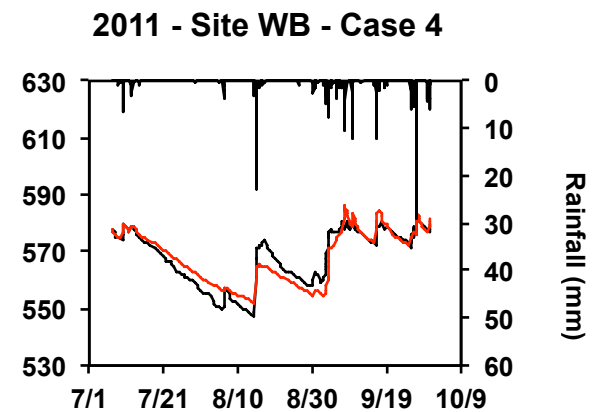
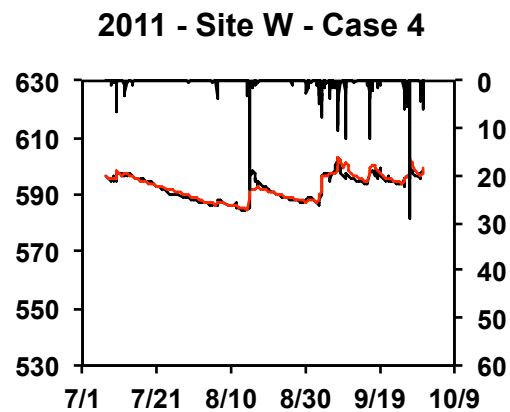
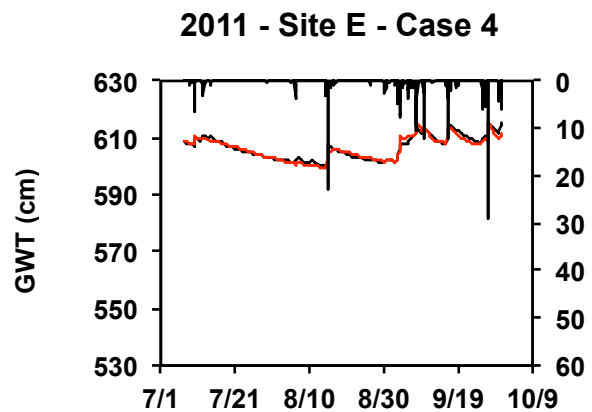
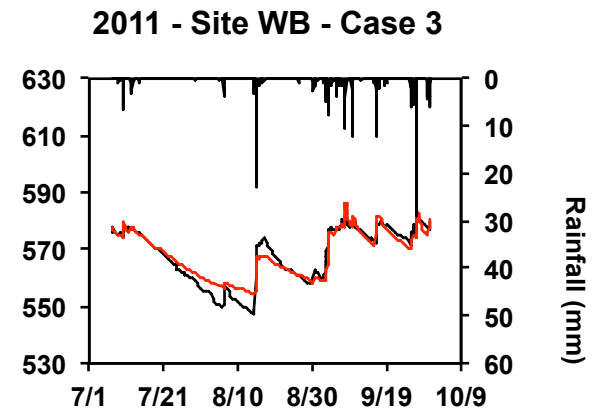
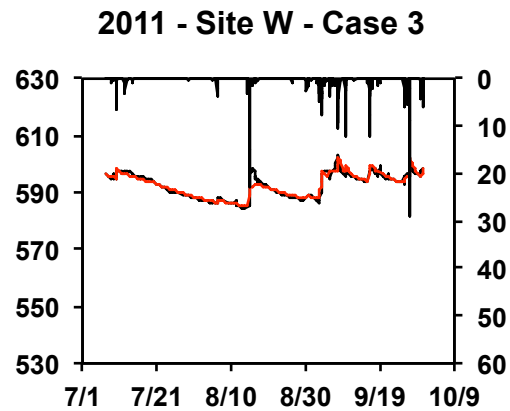
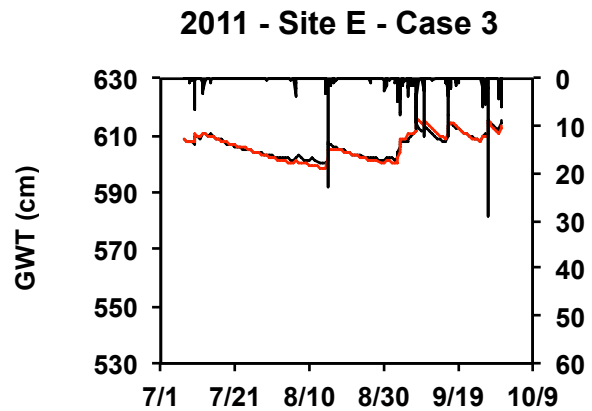


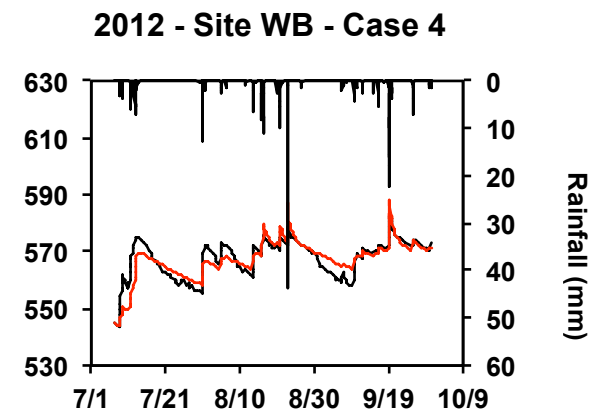
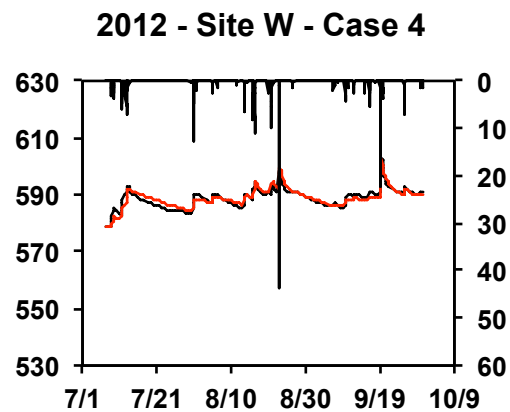
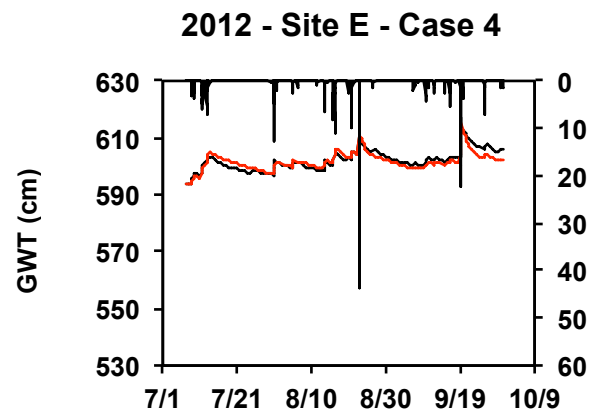
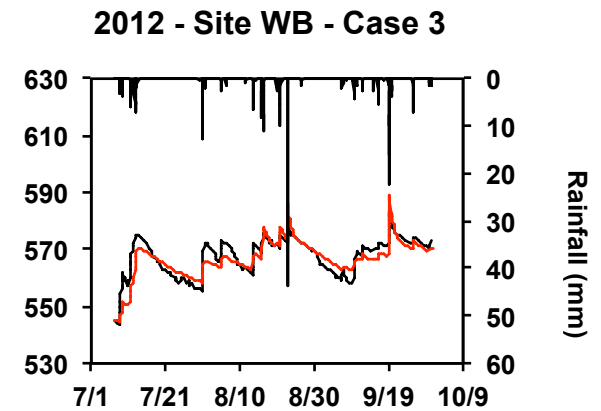
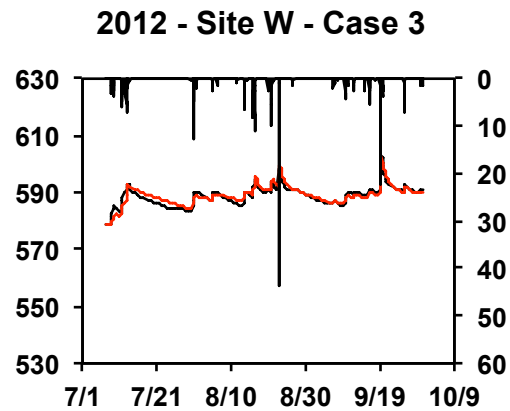
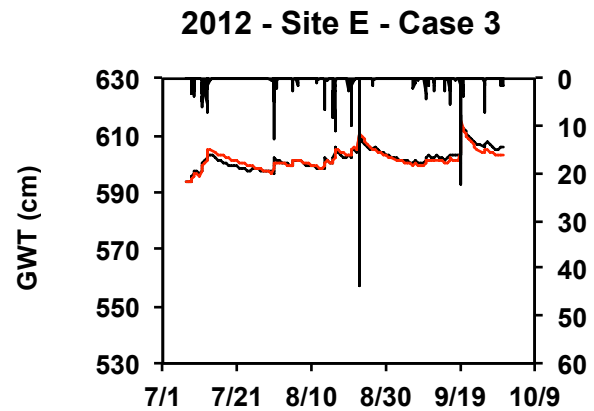


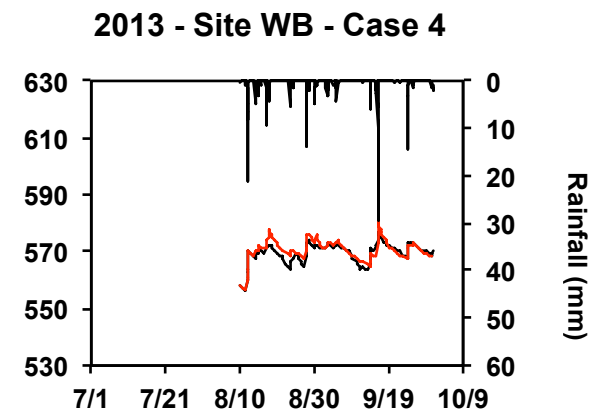
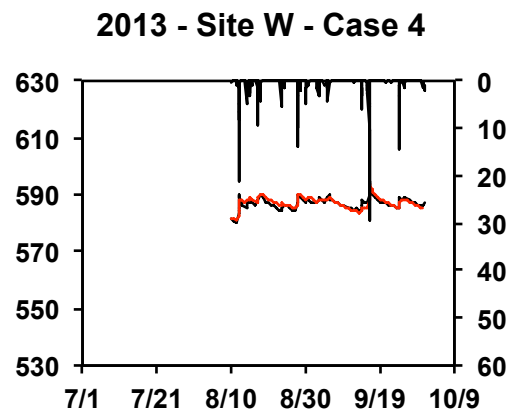
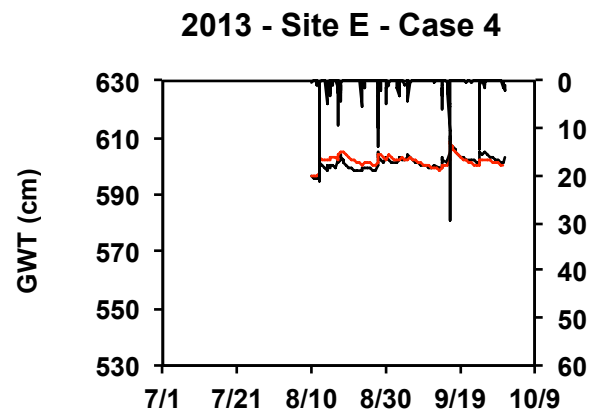
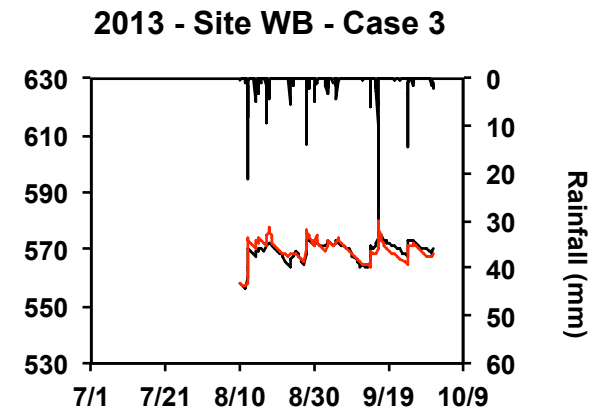
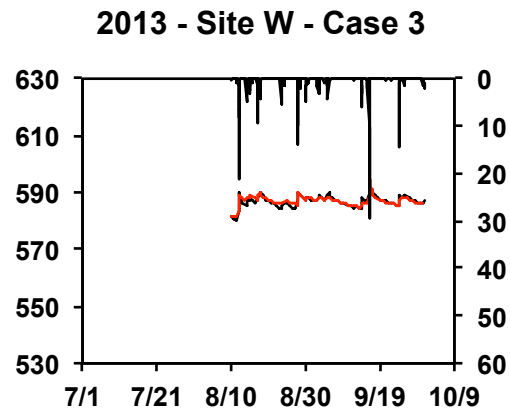
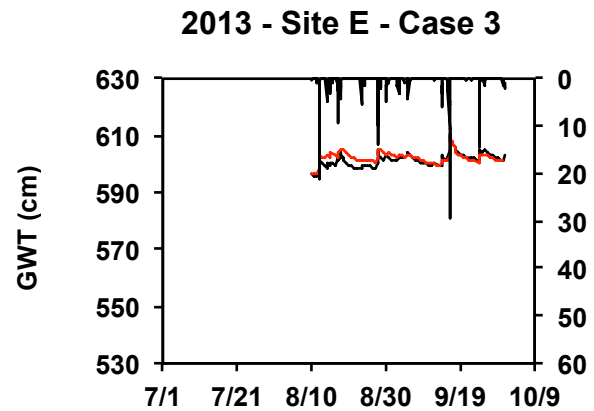






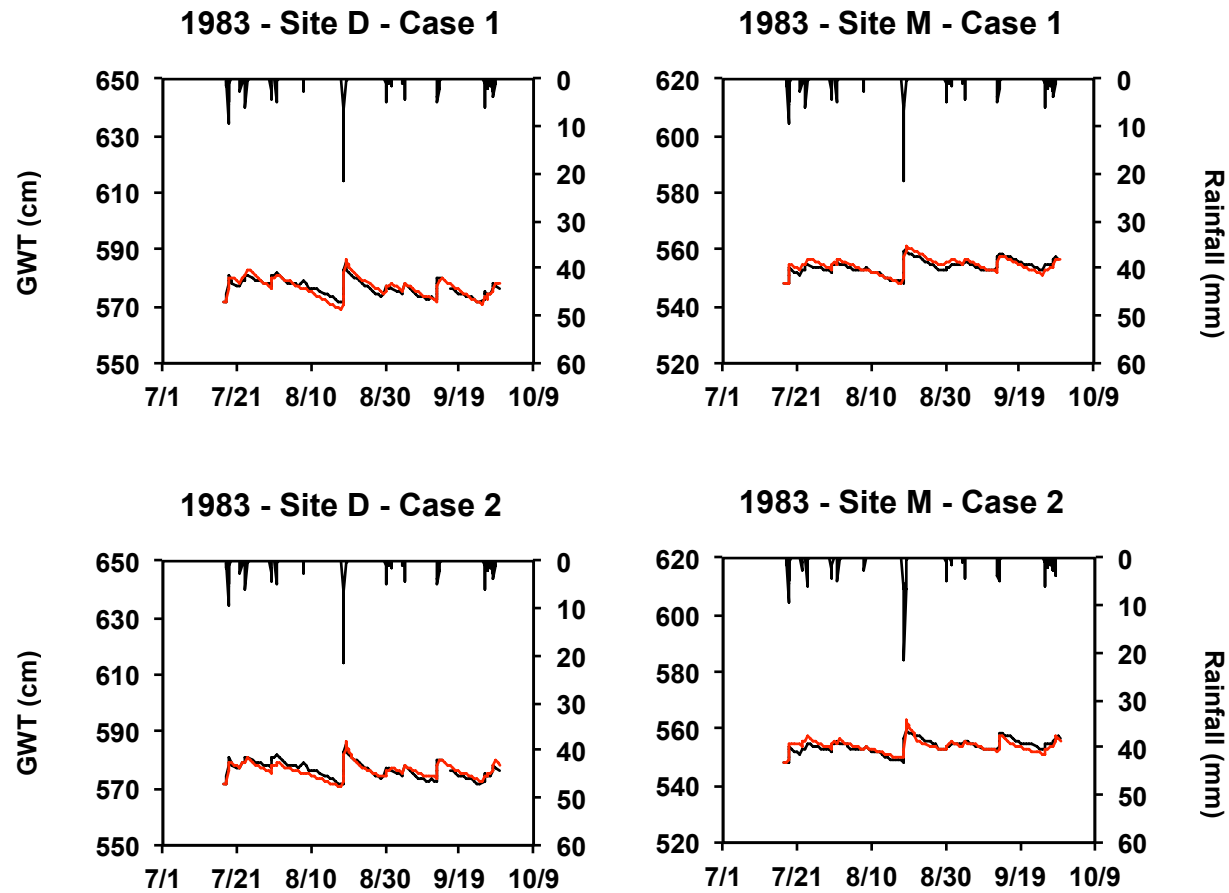




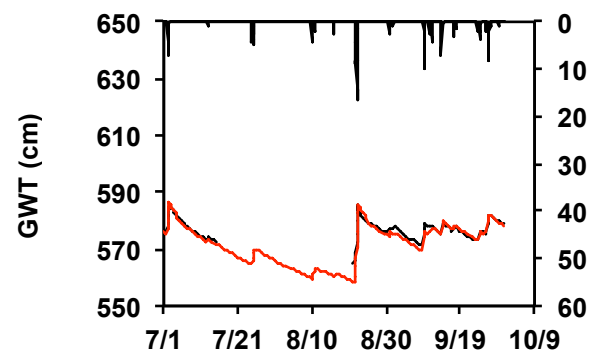


APPENDIX FIGURES

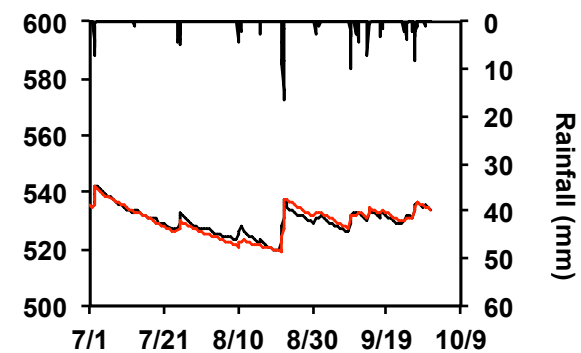
Figure 2. Simulation results of Ochiai, Sarobestu Mire by original PTM



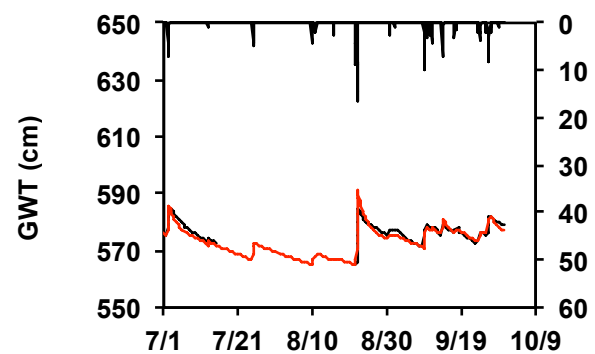
1984 - Site D - Case 1



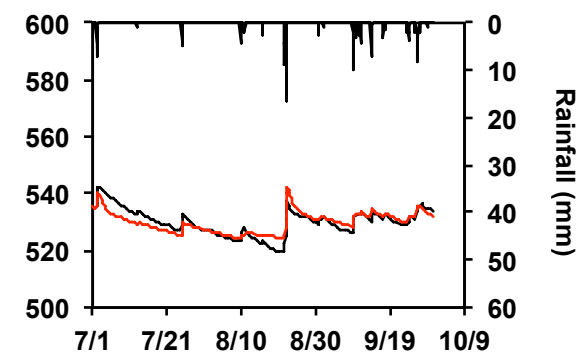
1984 - Site U - Case 1

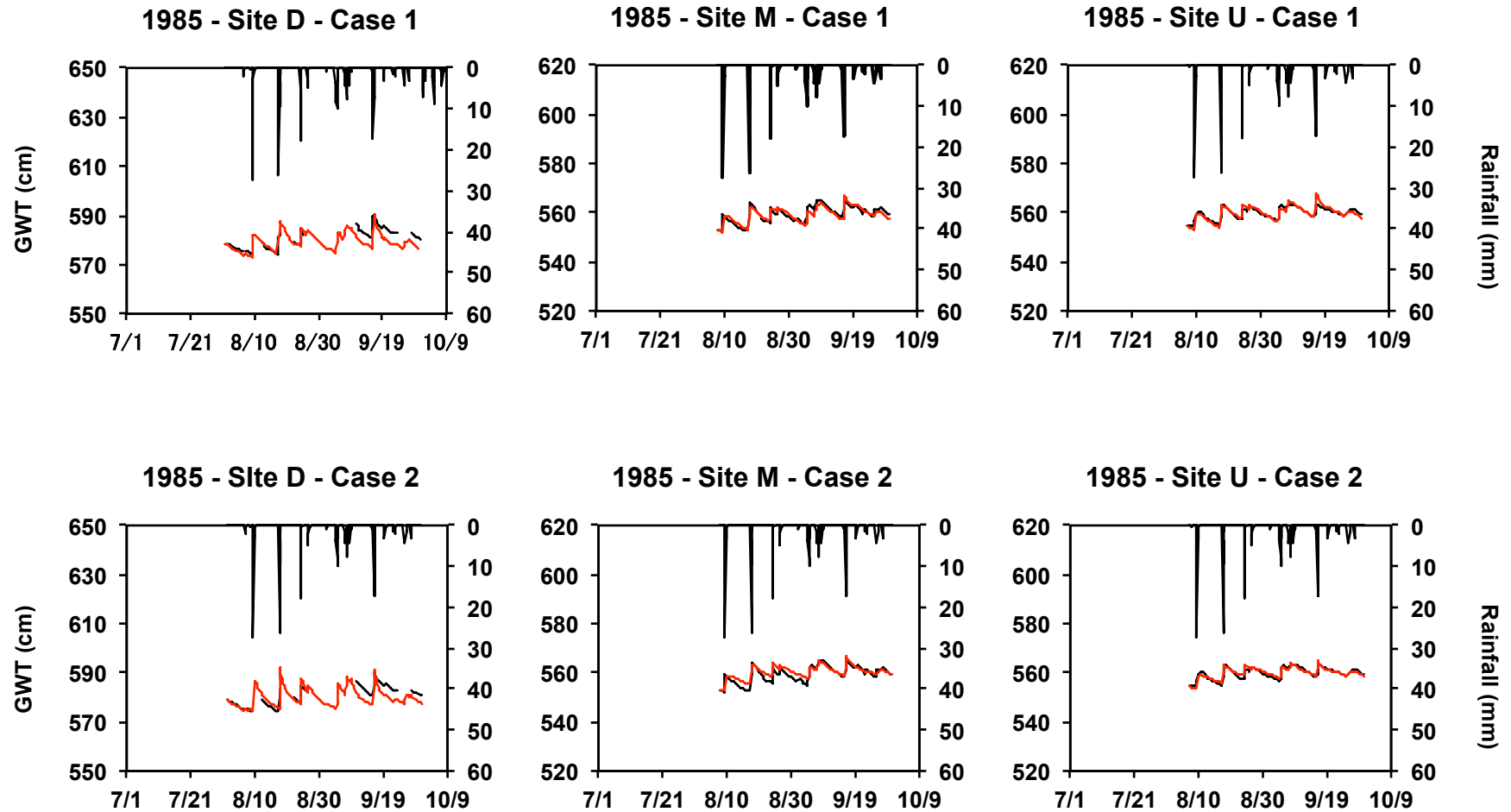


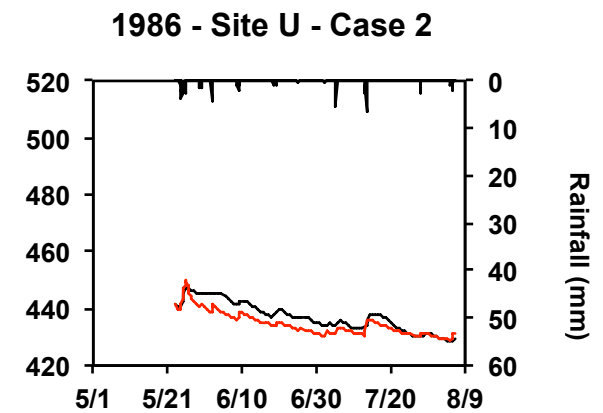
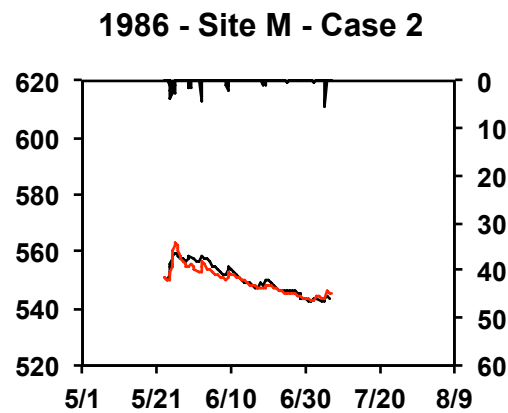
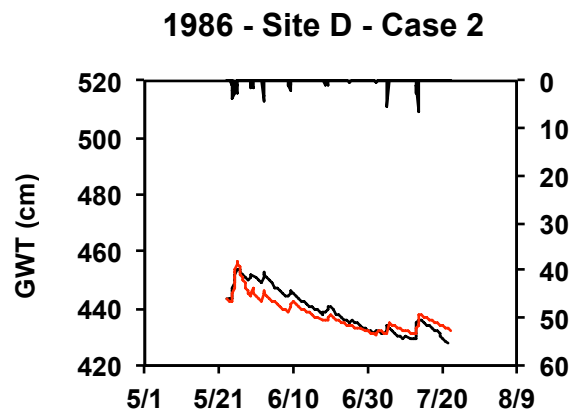
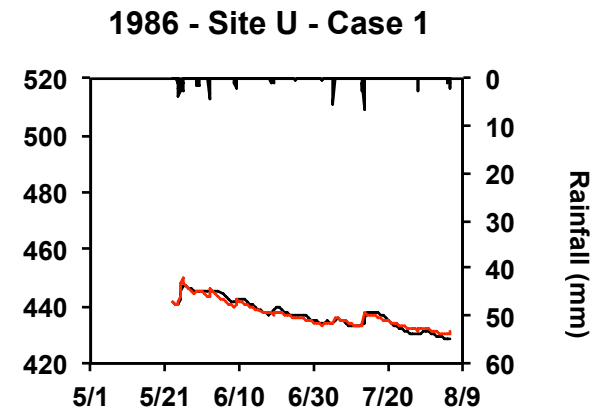
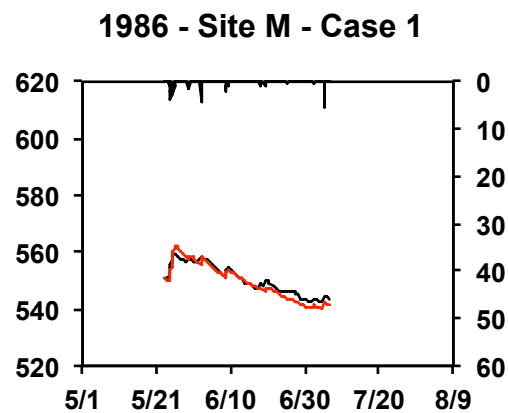
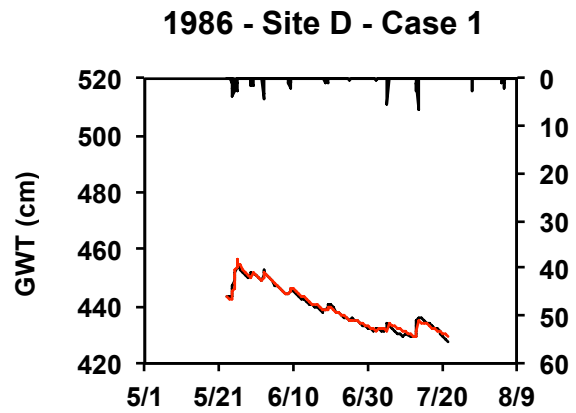
1984 - Site D - Case 2

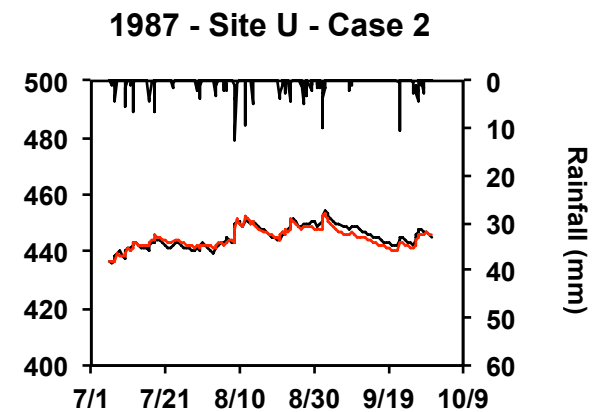
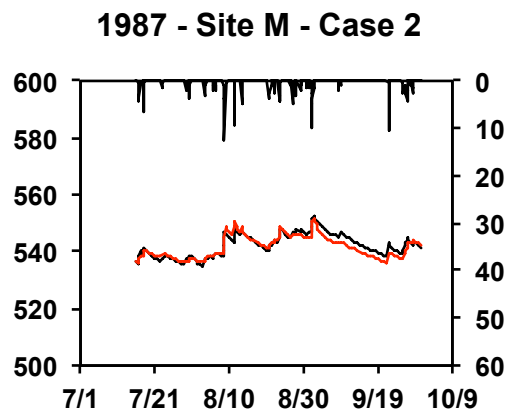
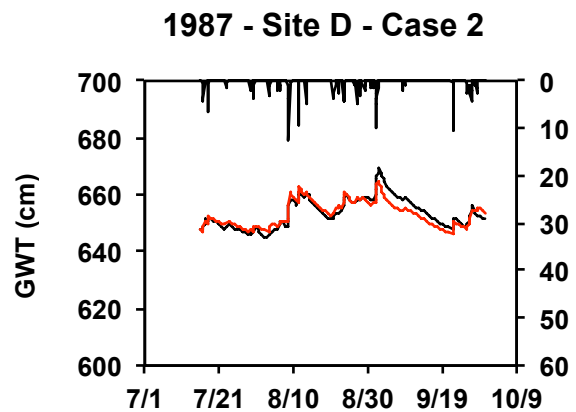
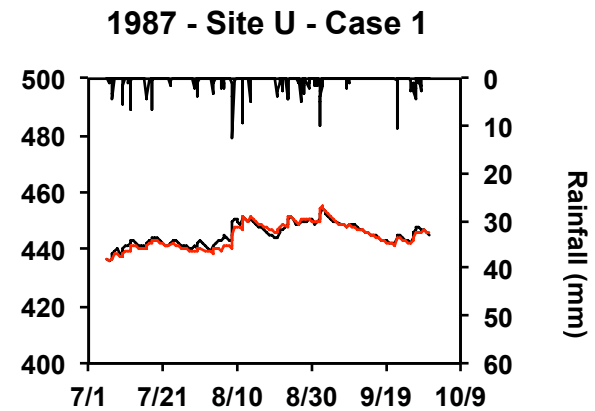
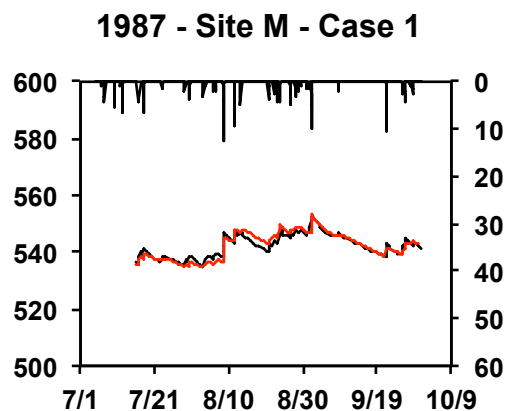
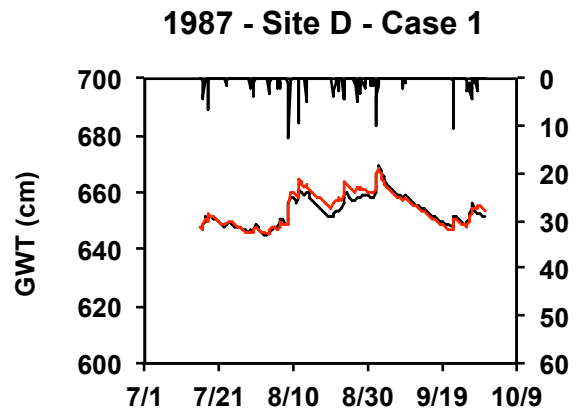


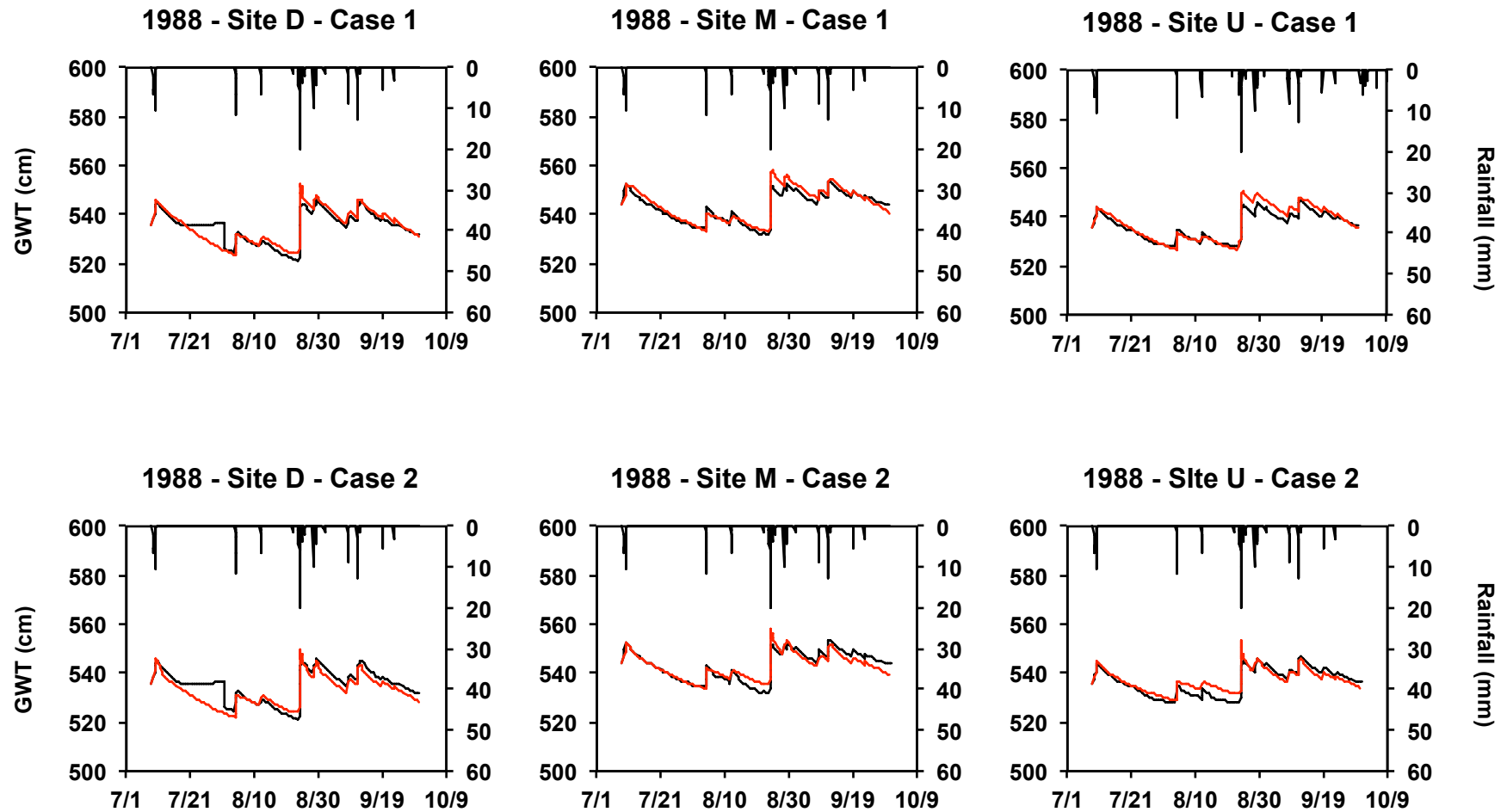
1984 - Site U - Case 2

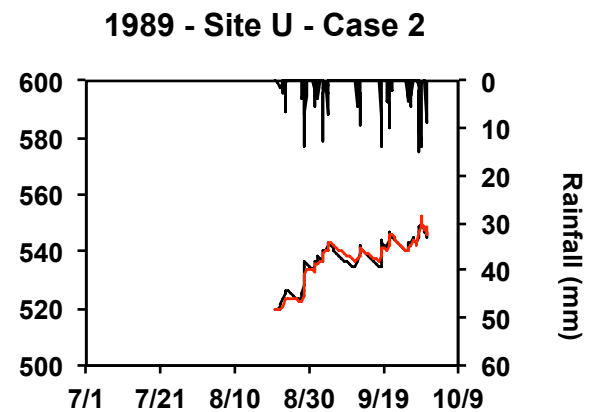
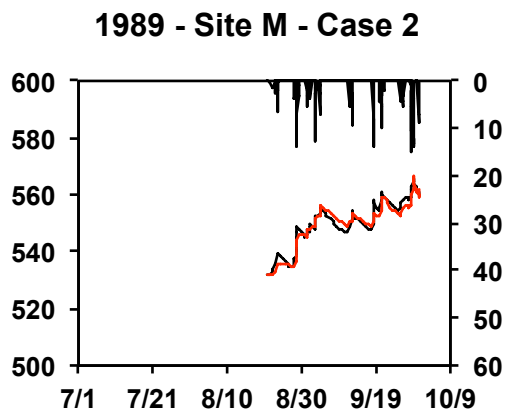
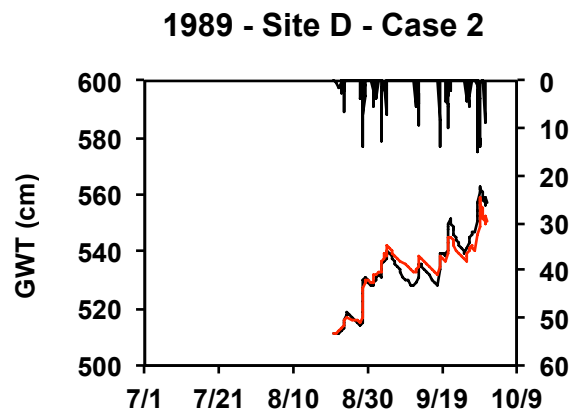
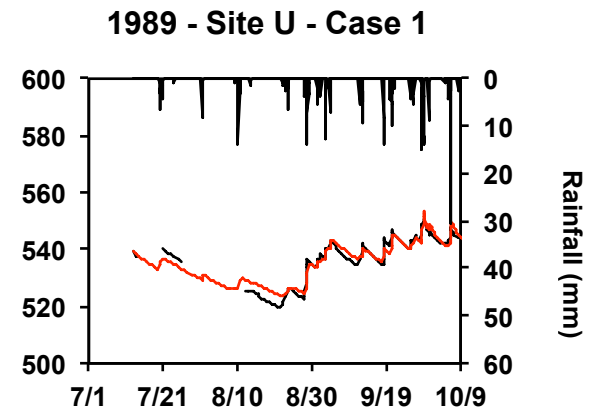
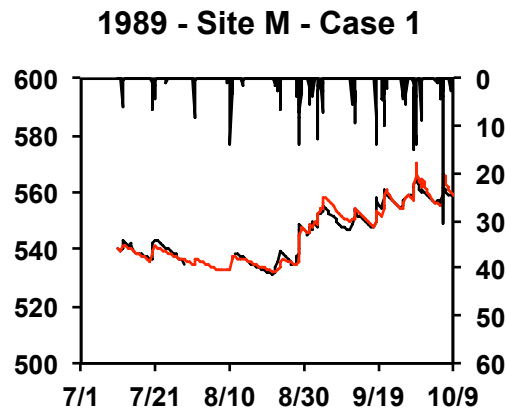
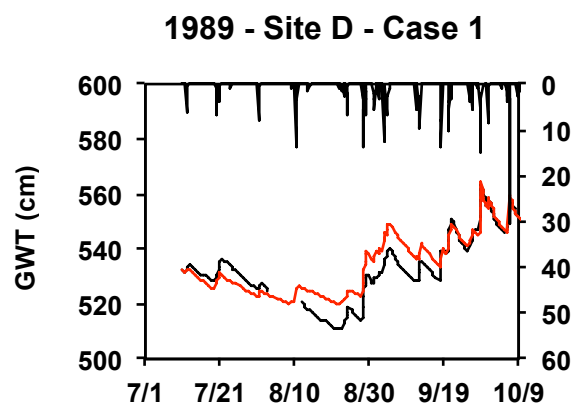


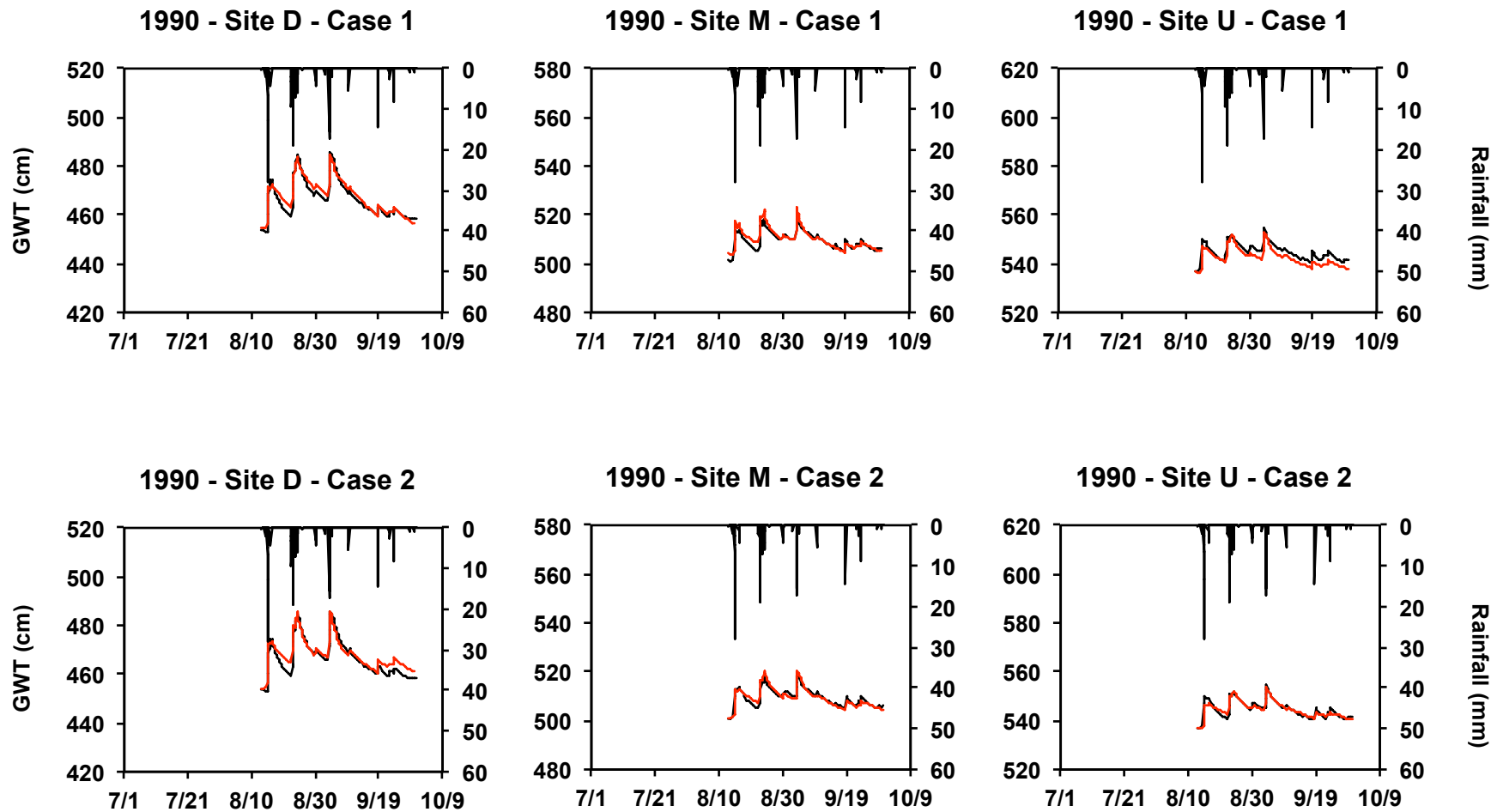


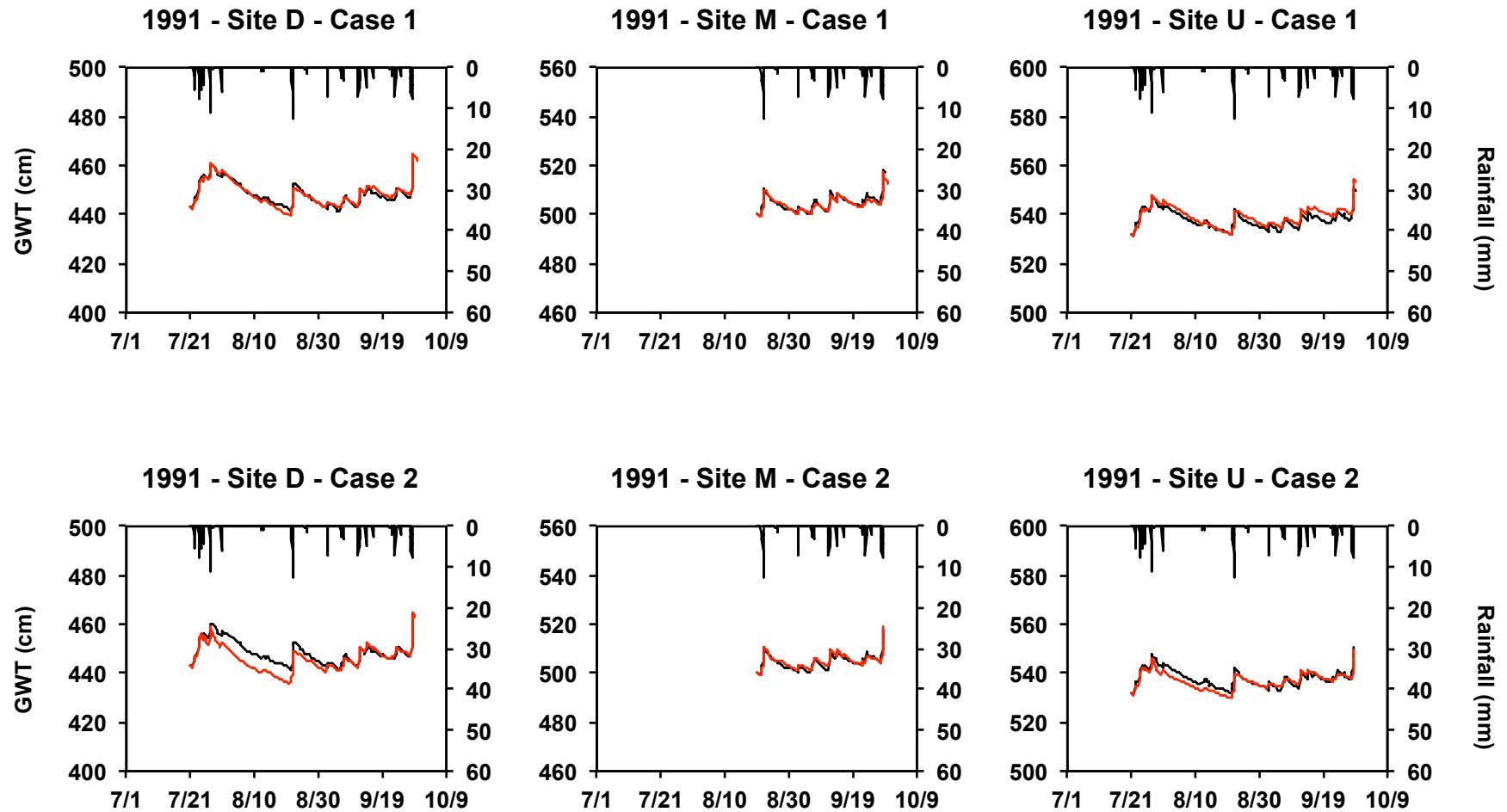


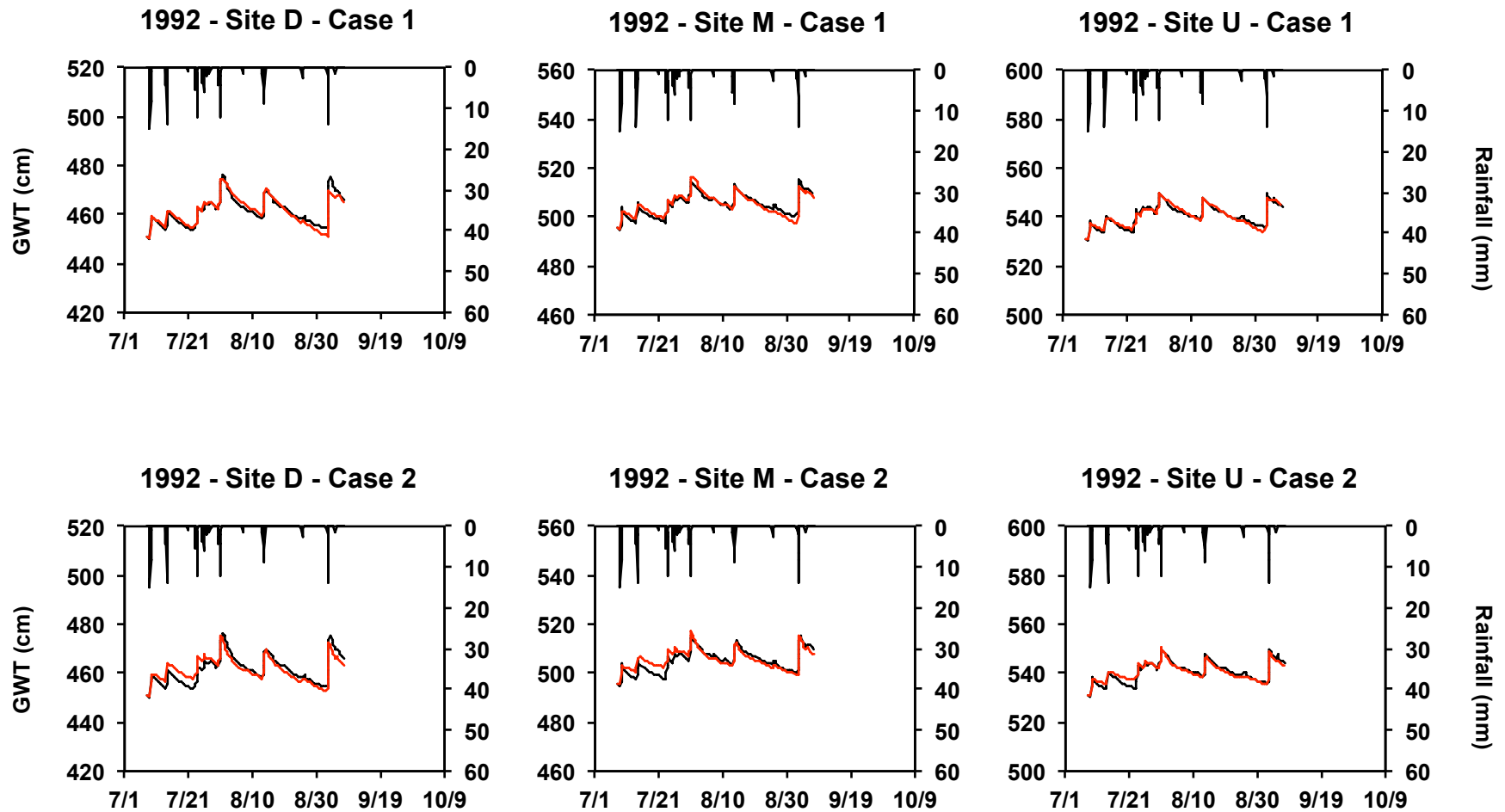


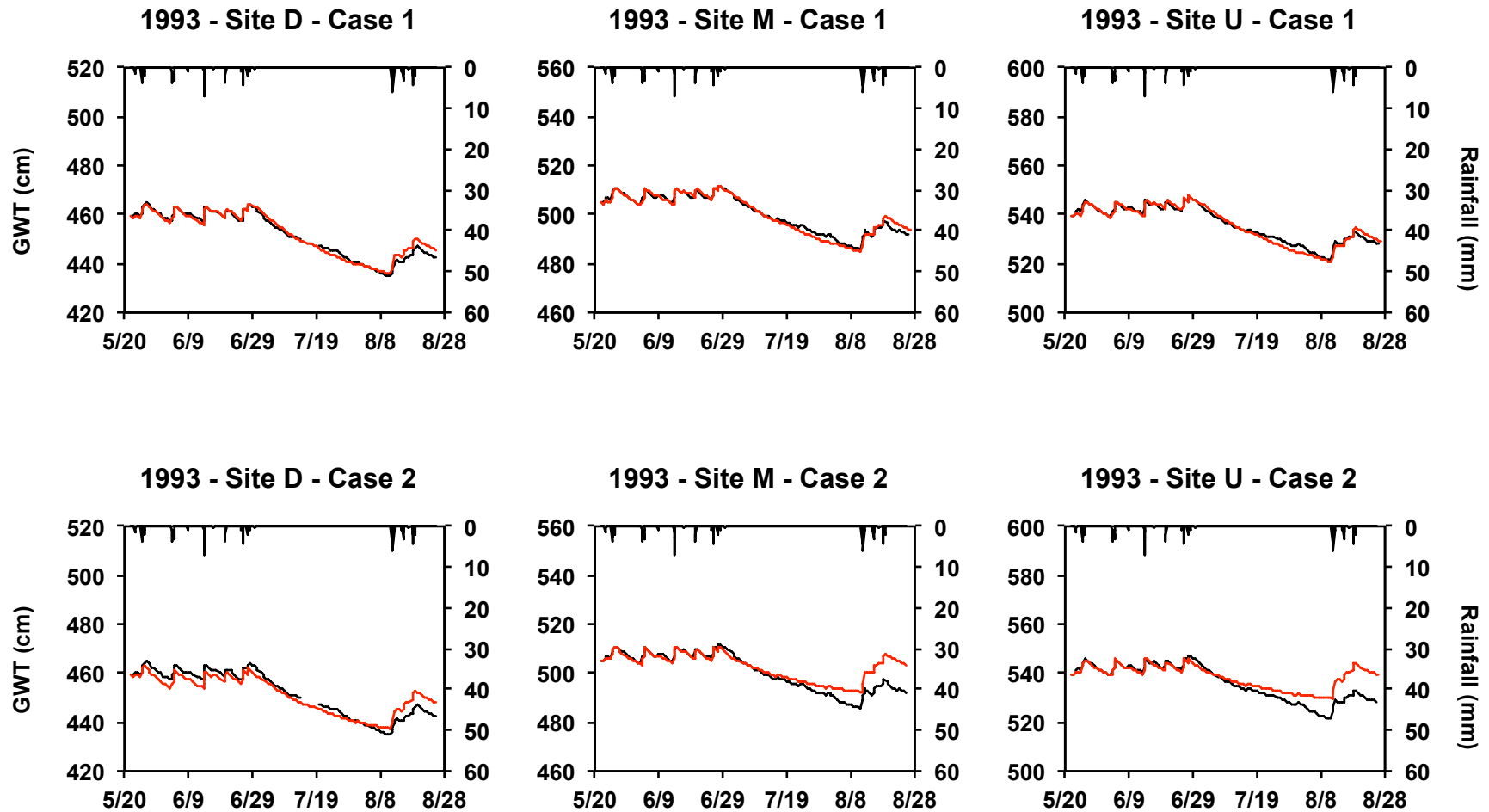


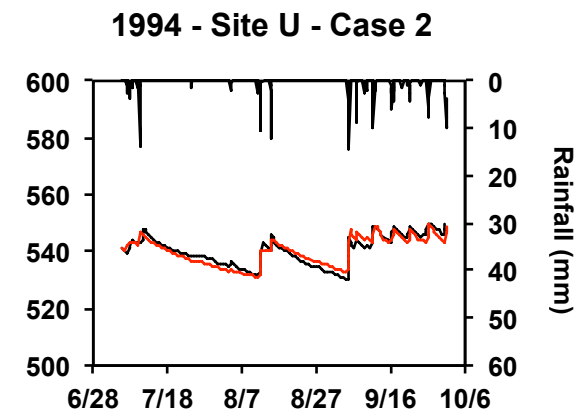
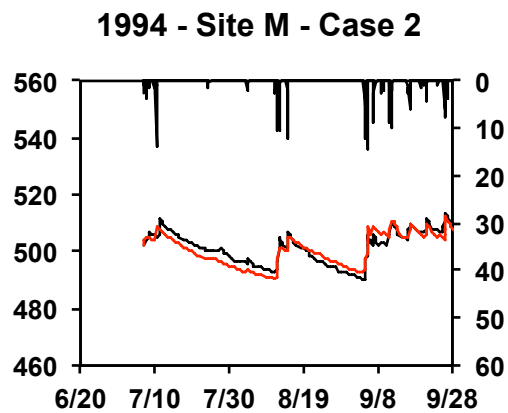
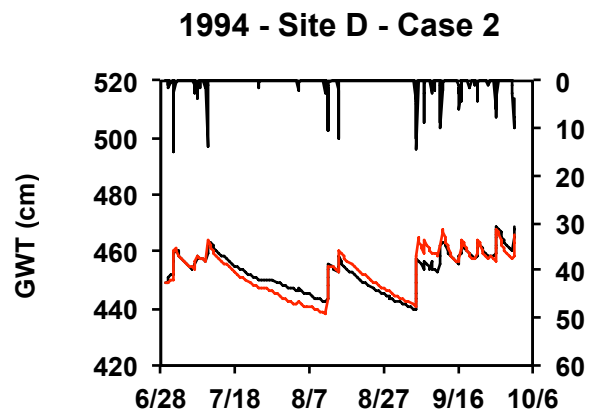
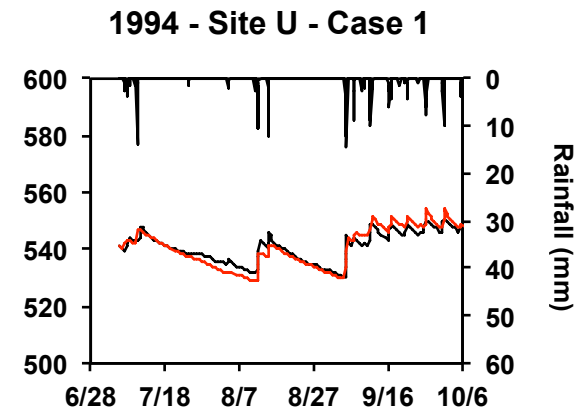
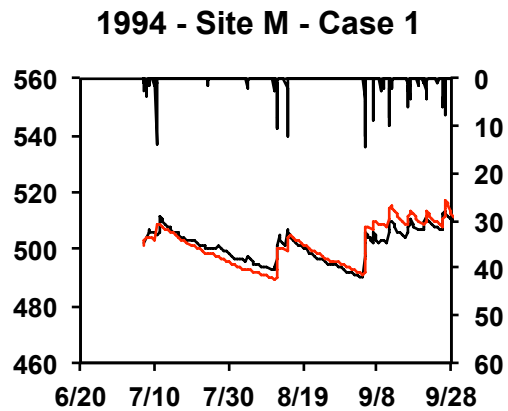
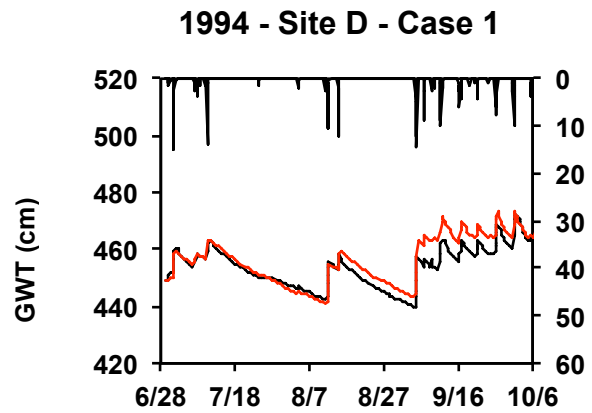


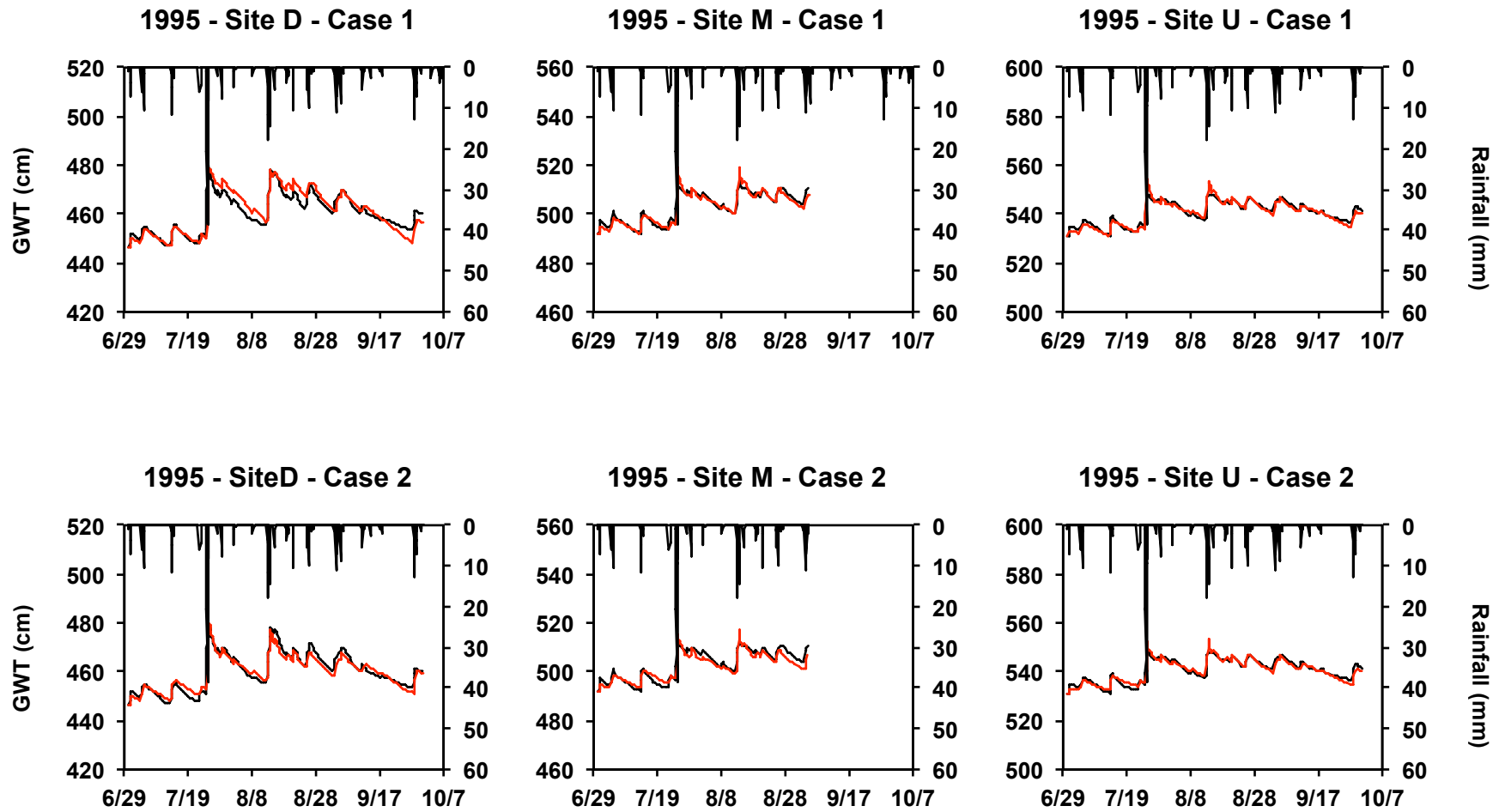


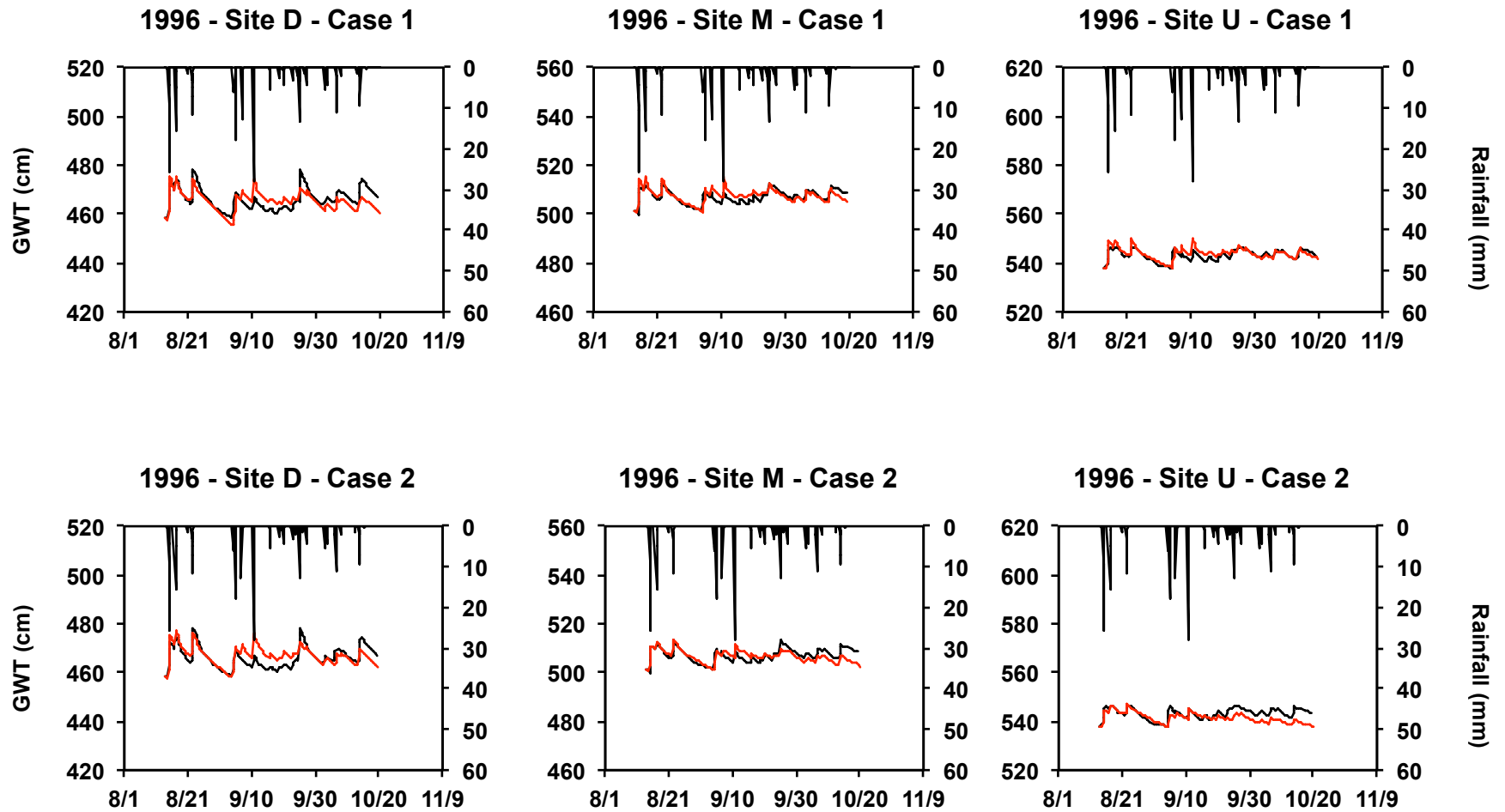


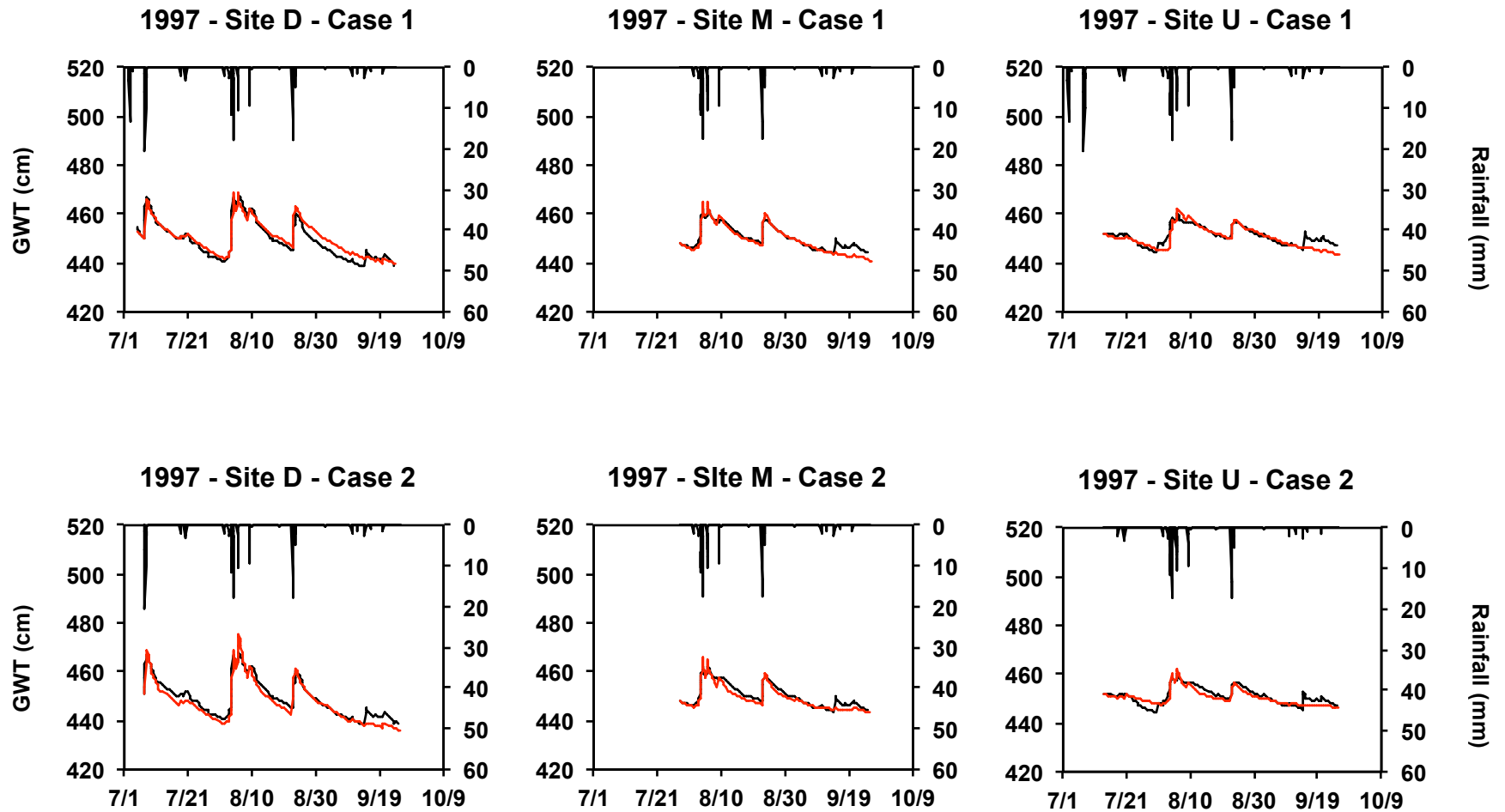


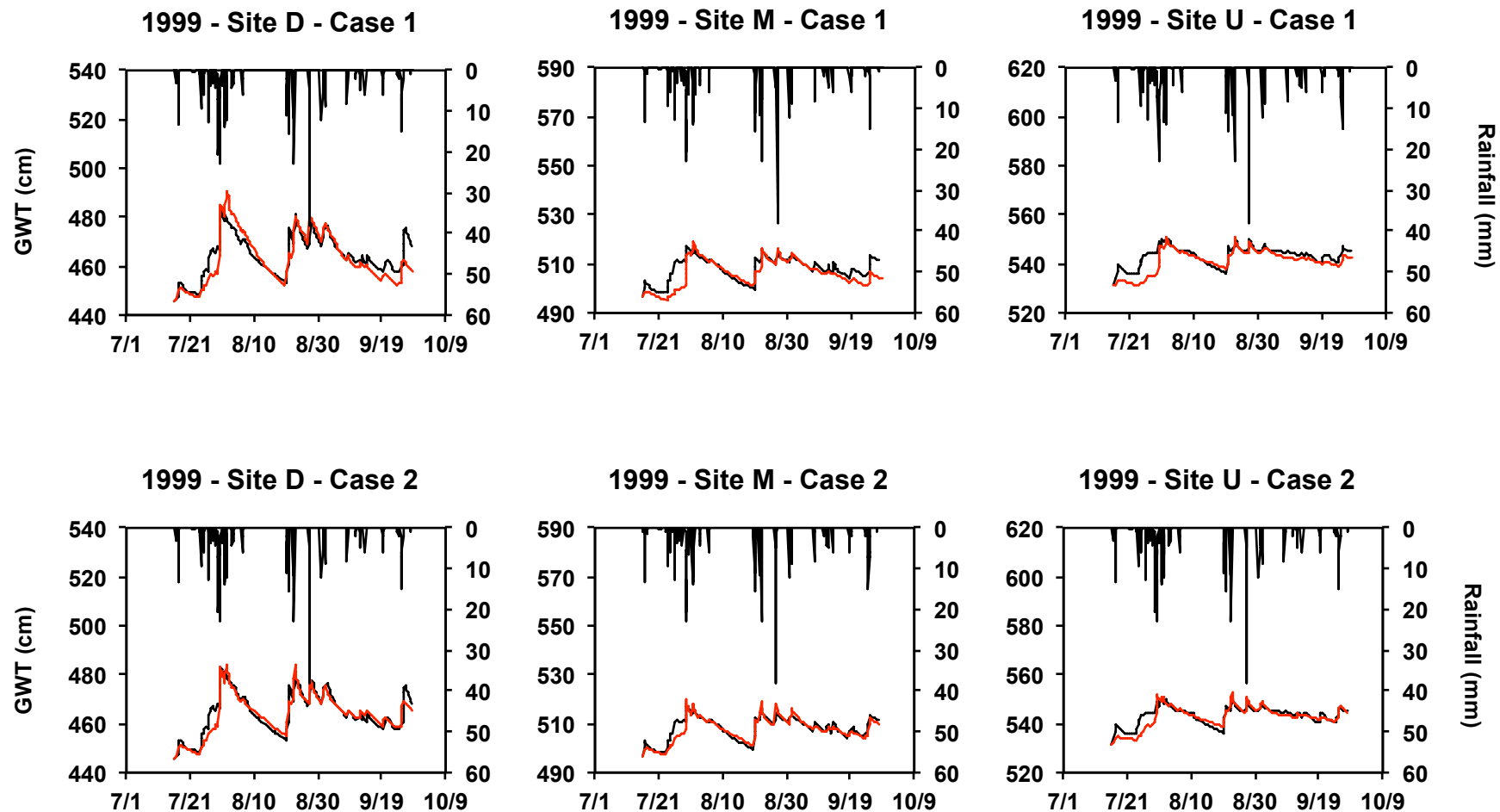


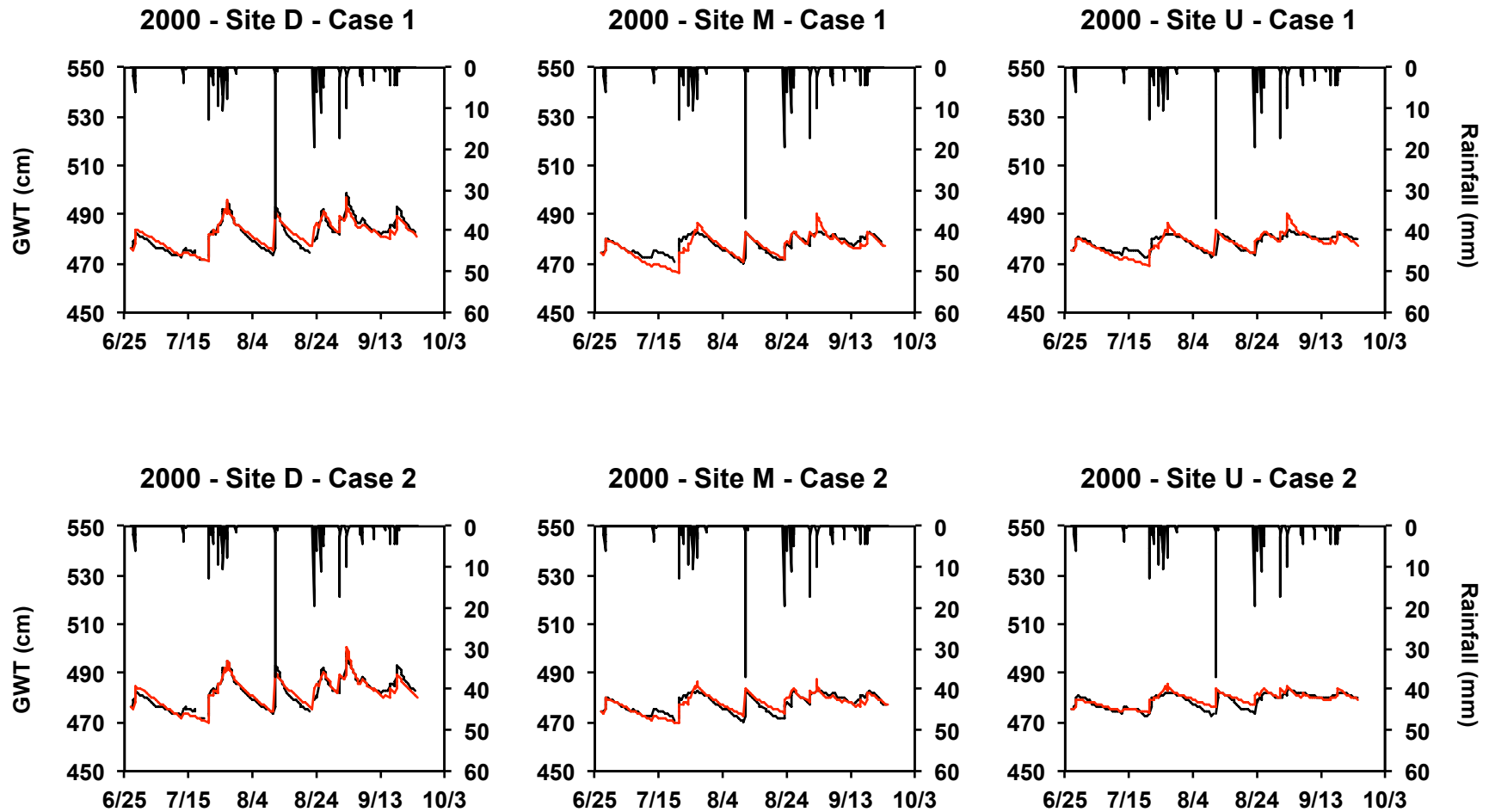


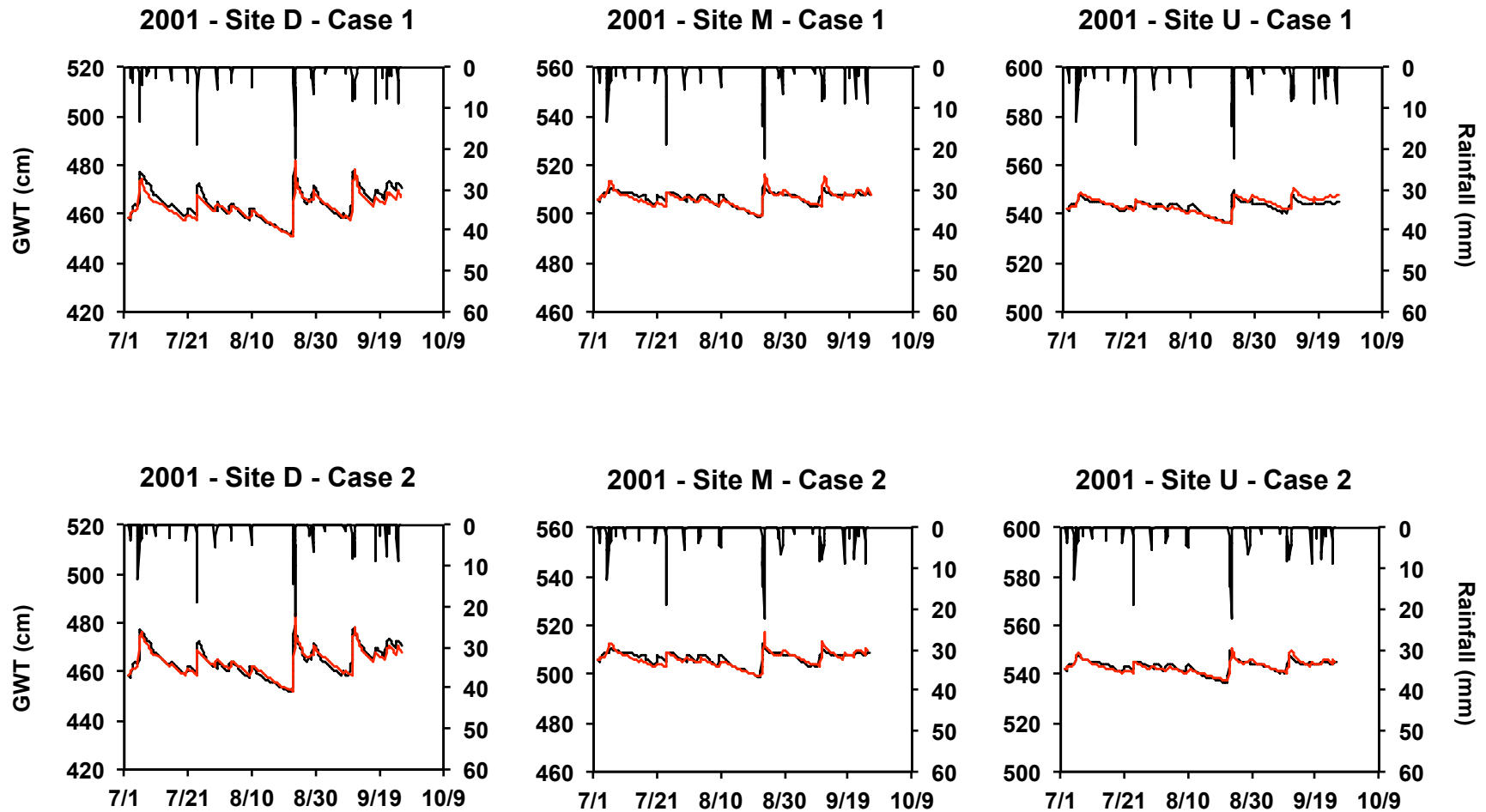


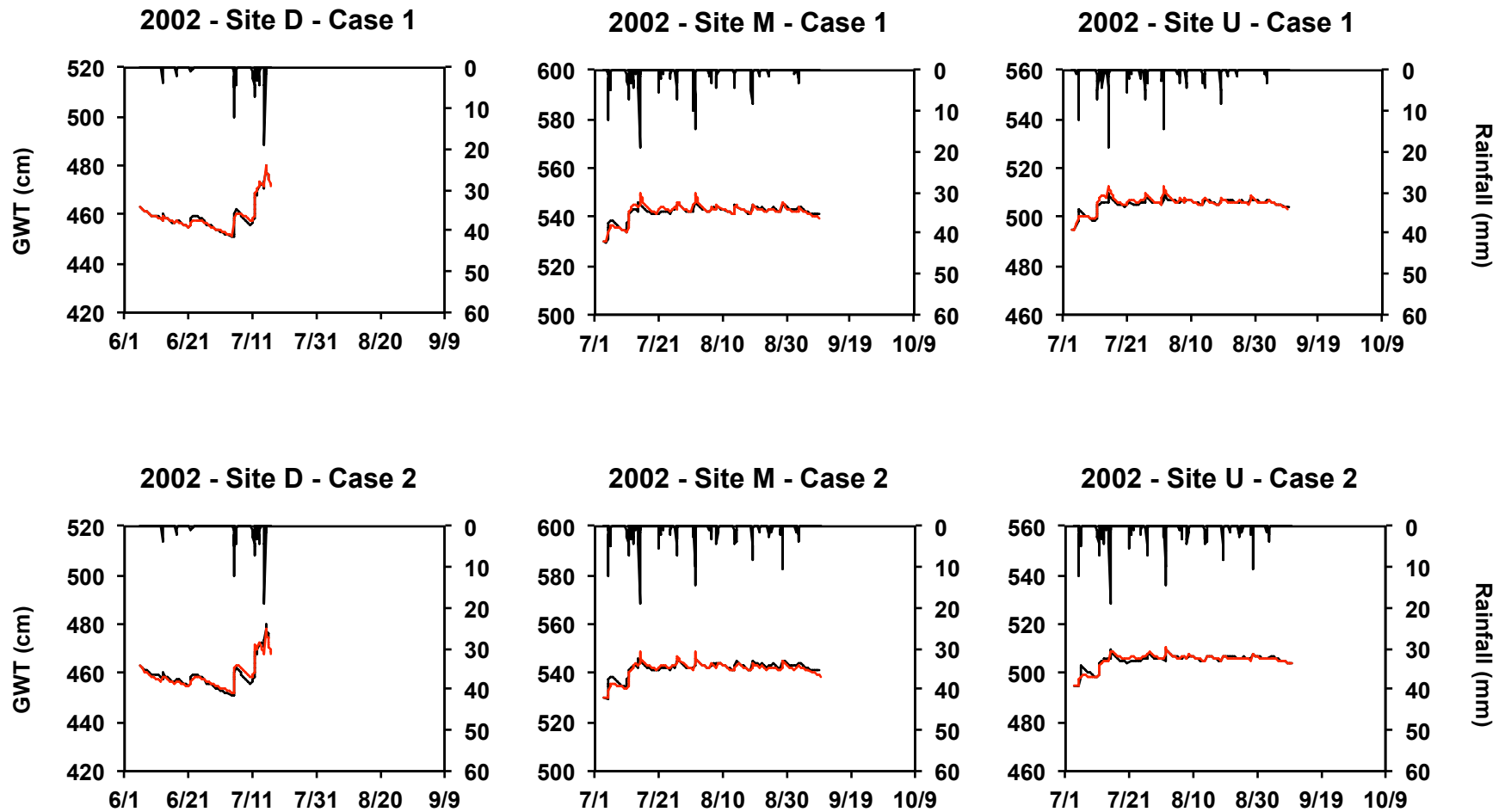


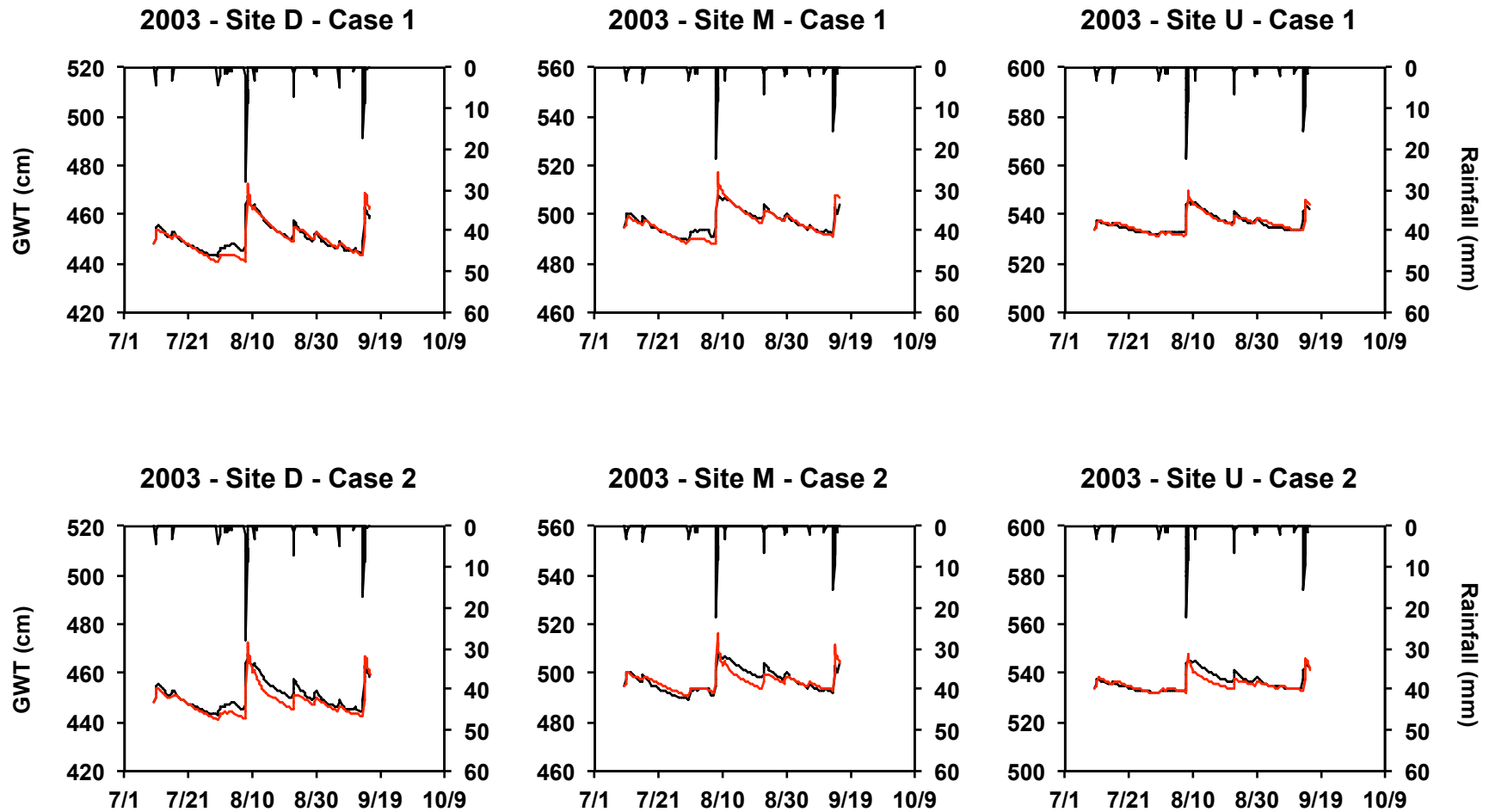


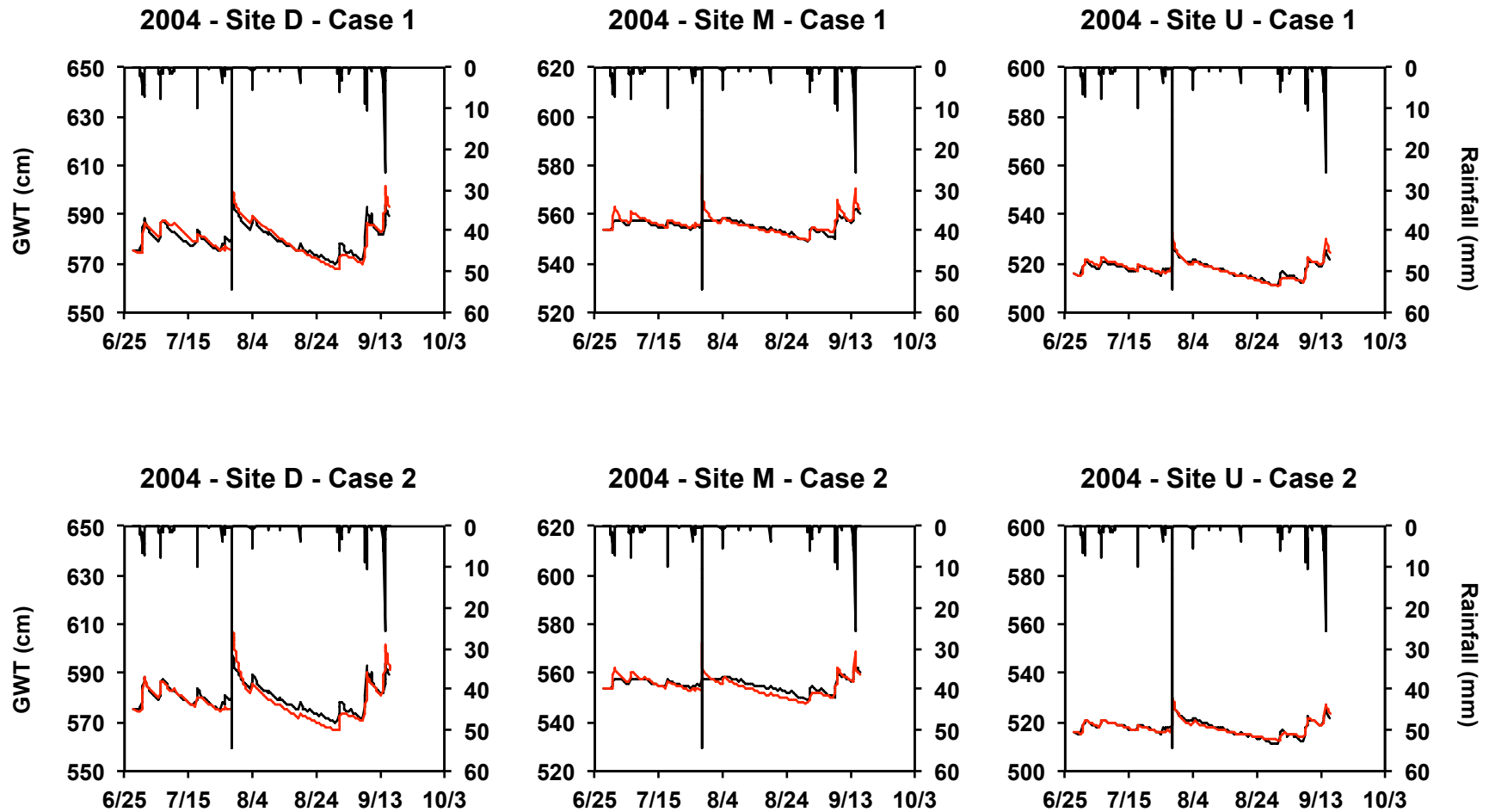


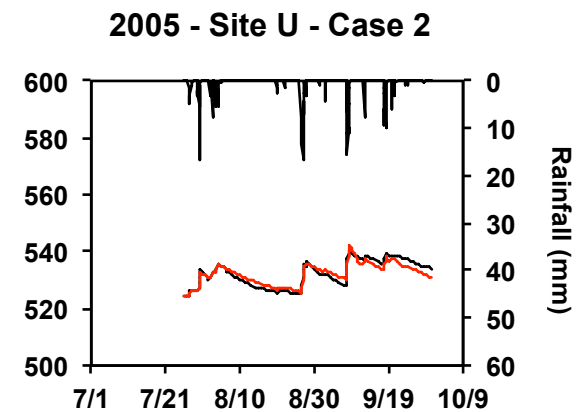
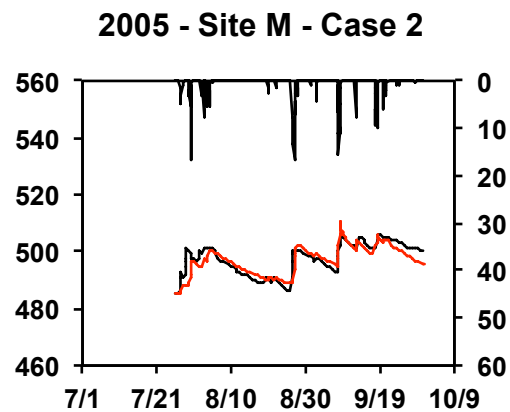
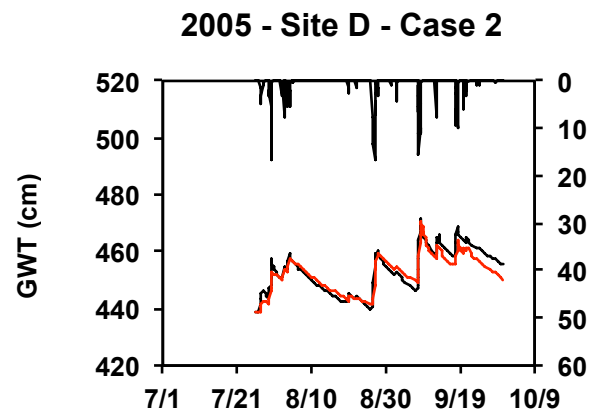
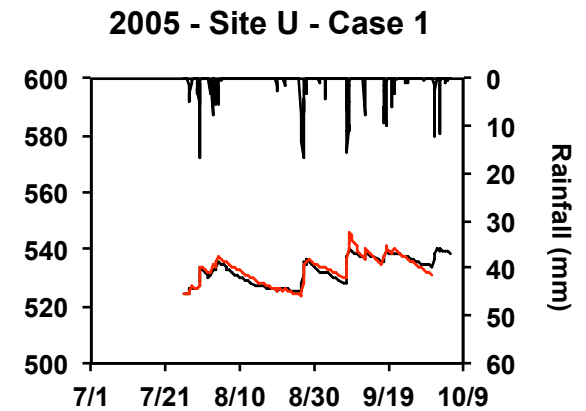
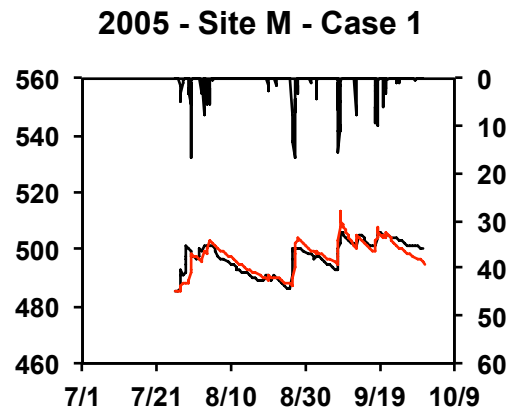
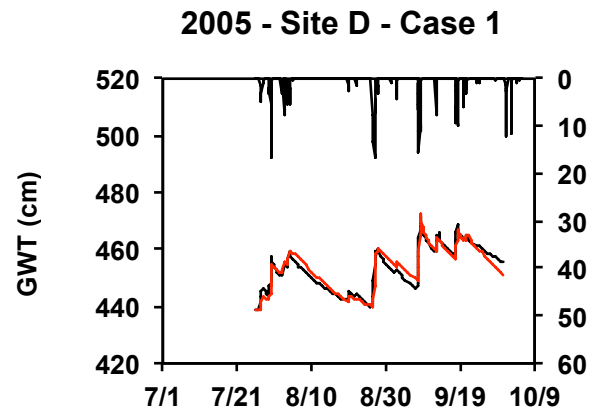


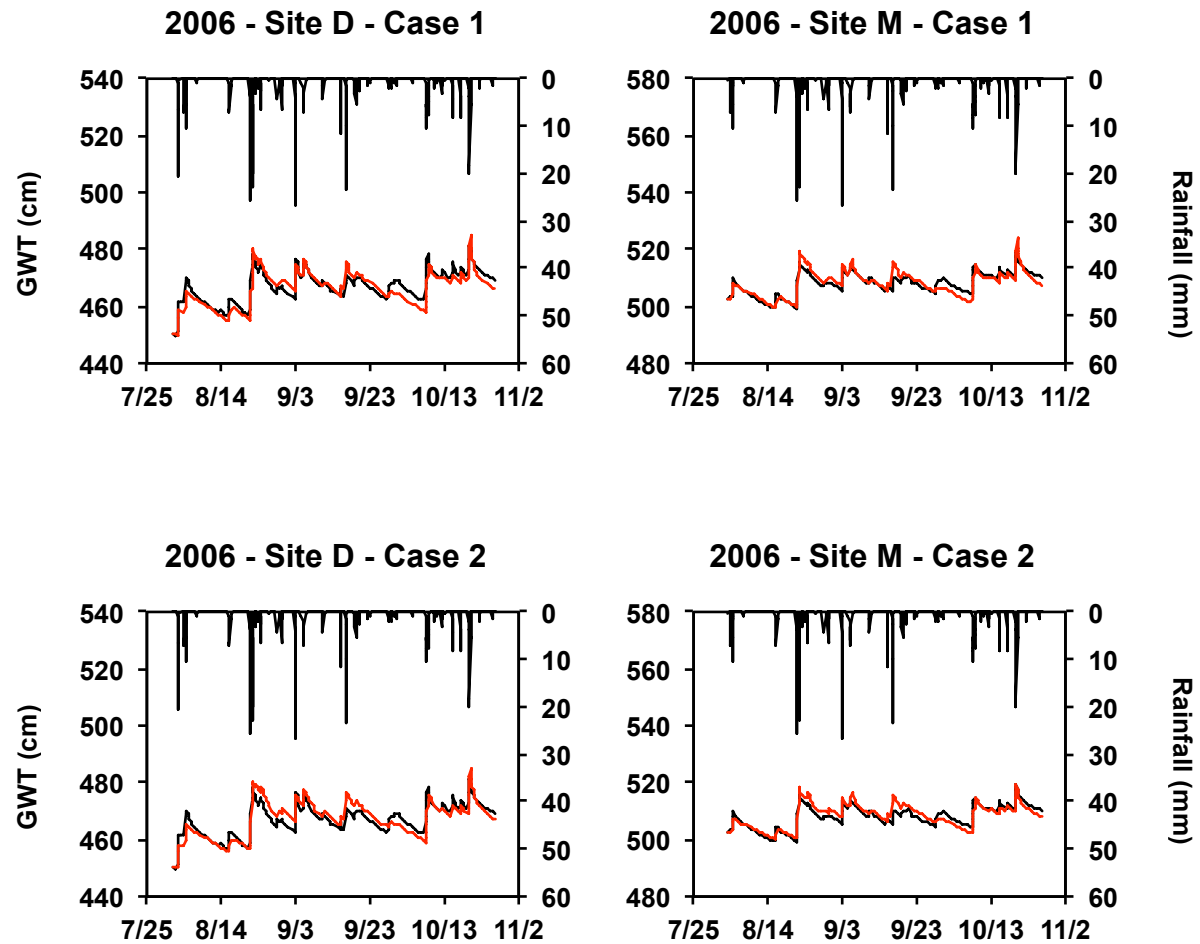


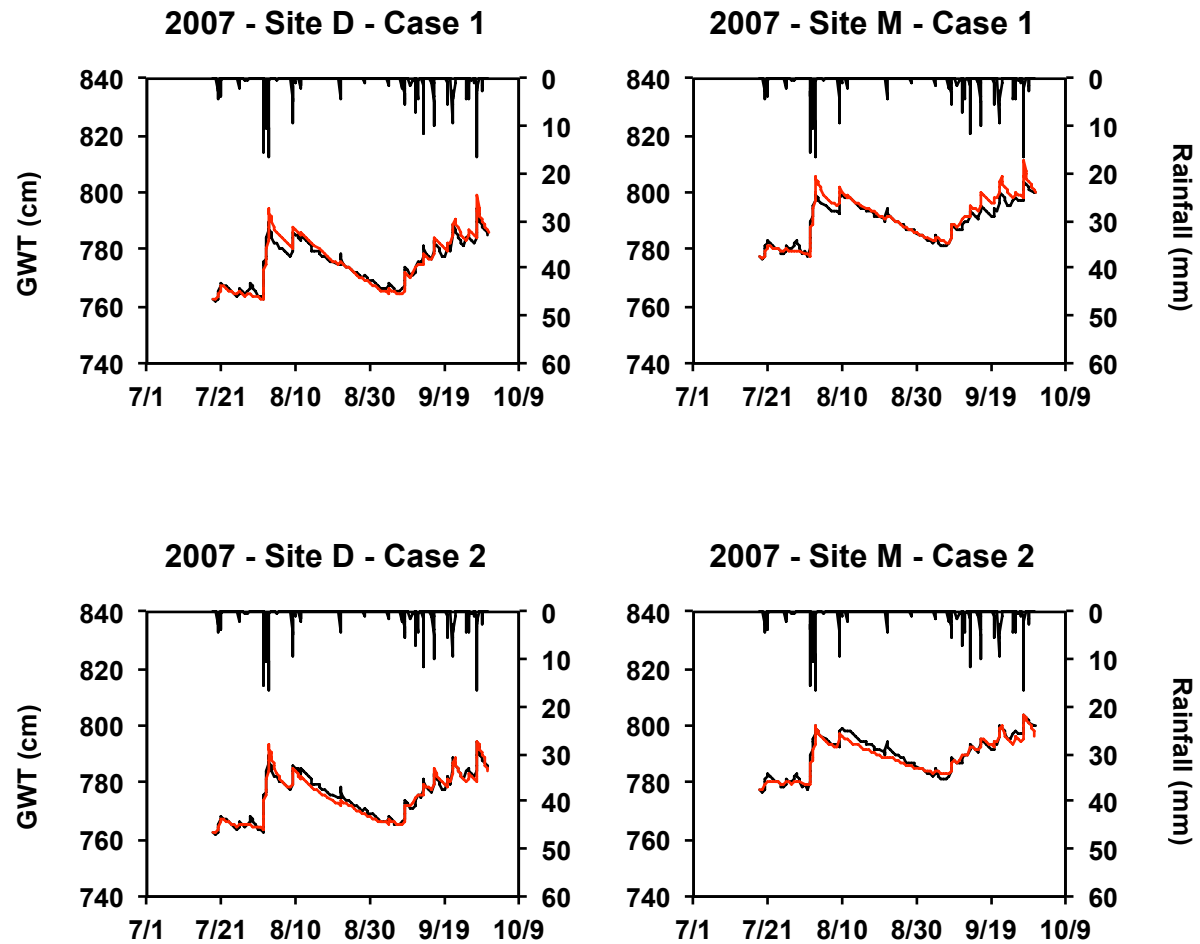


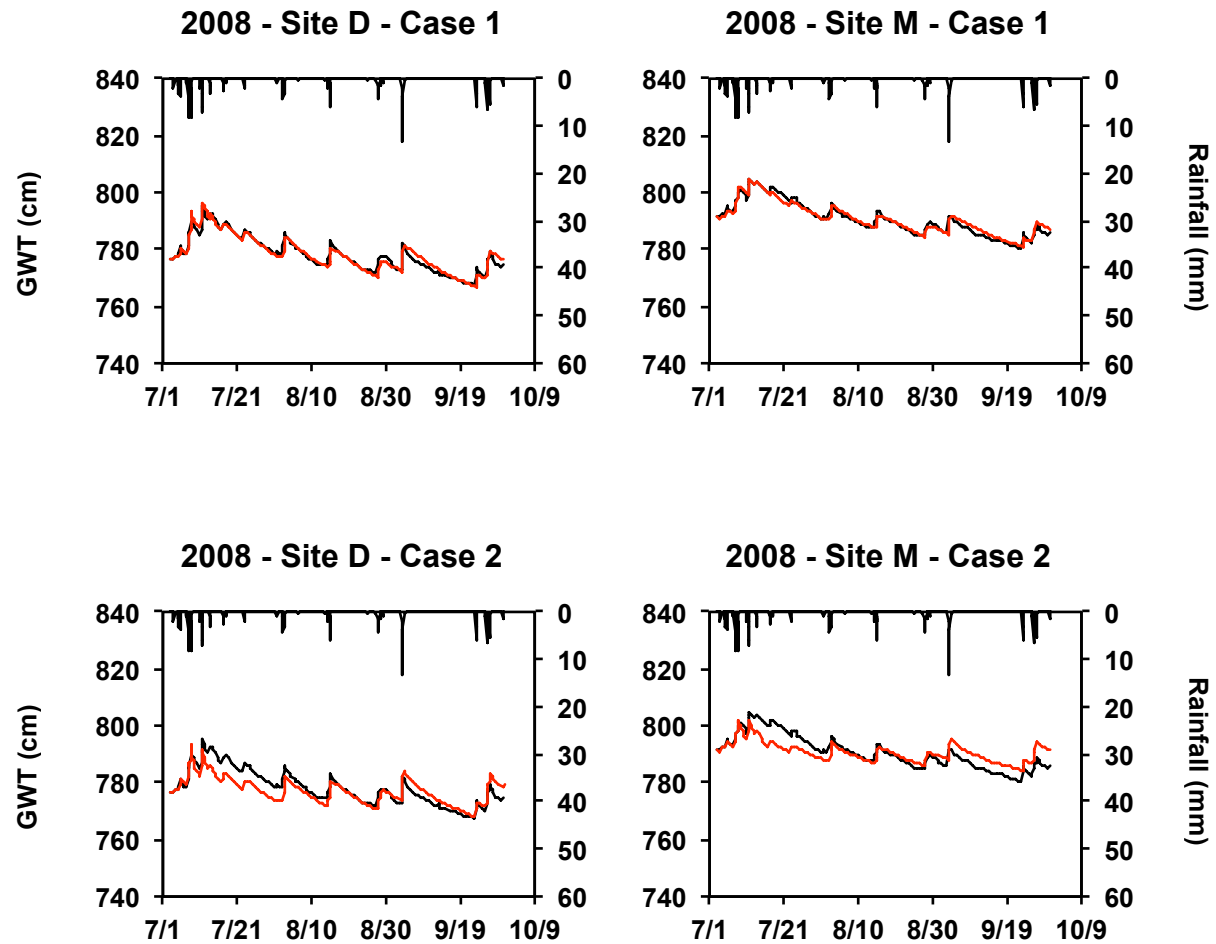


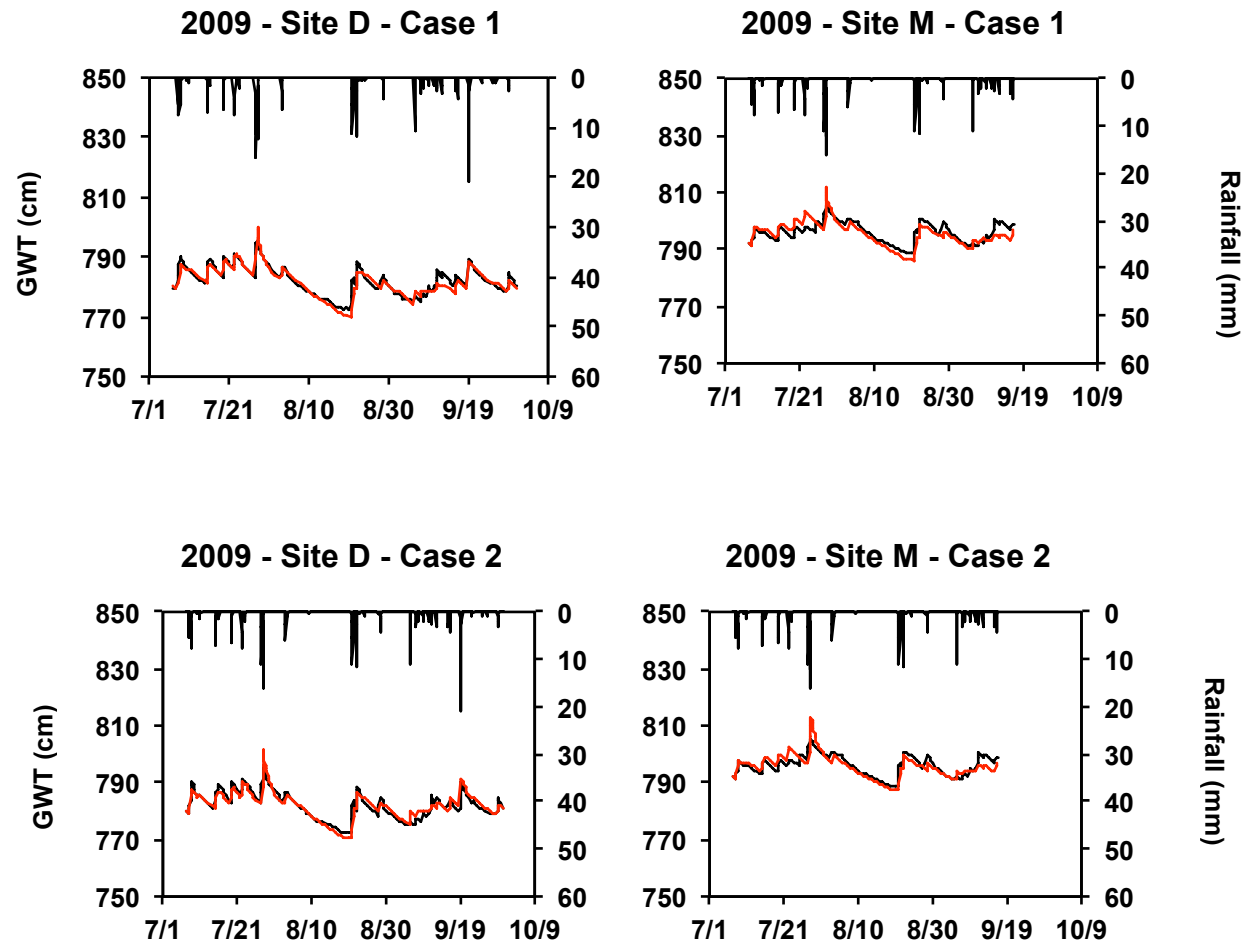


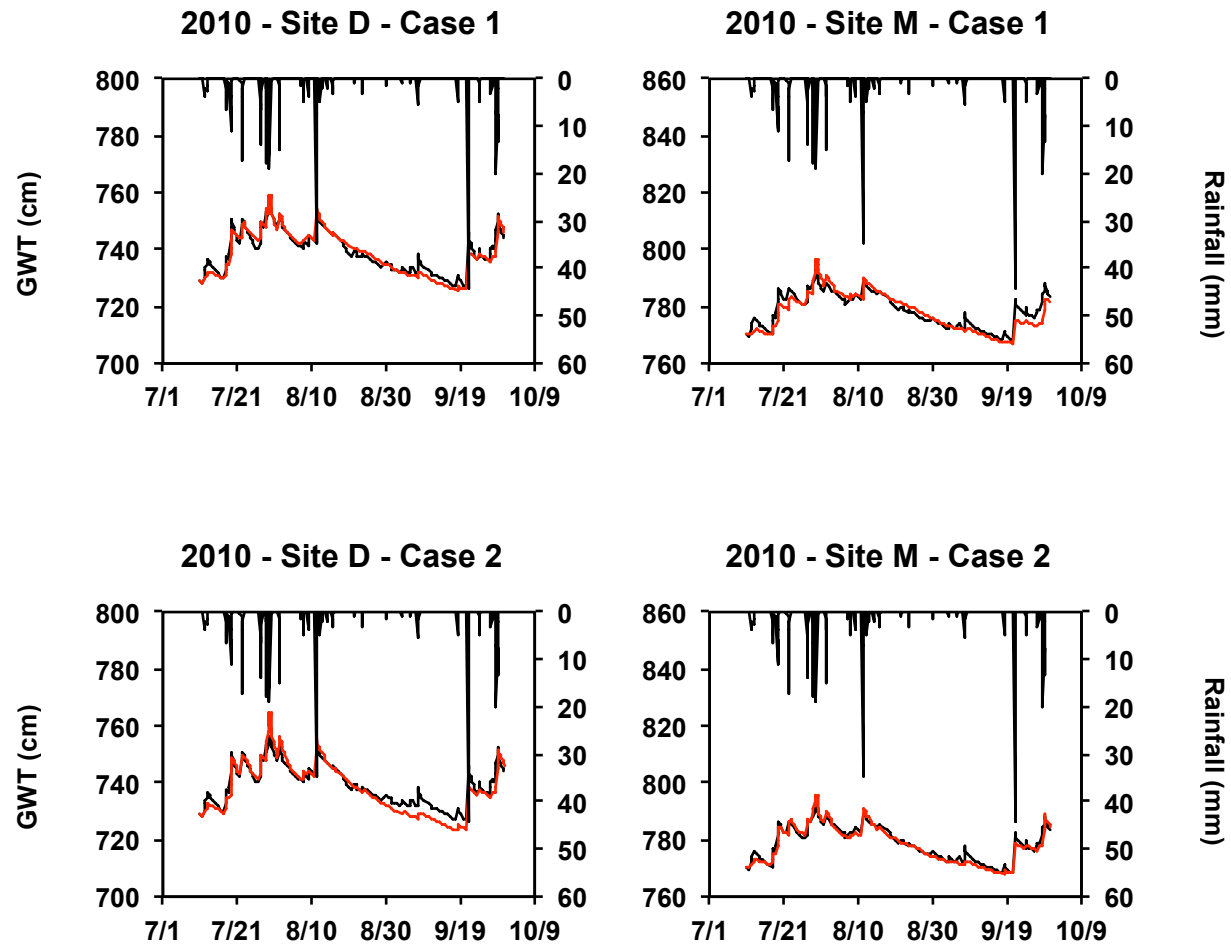


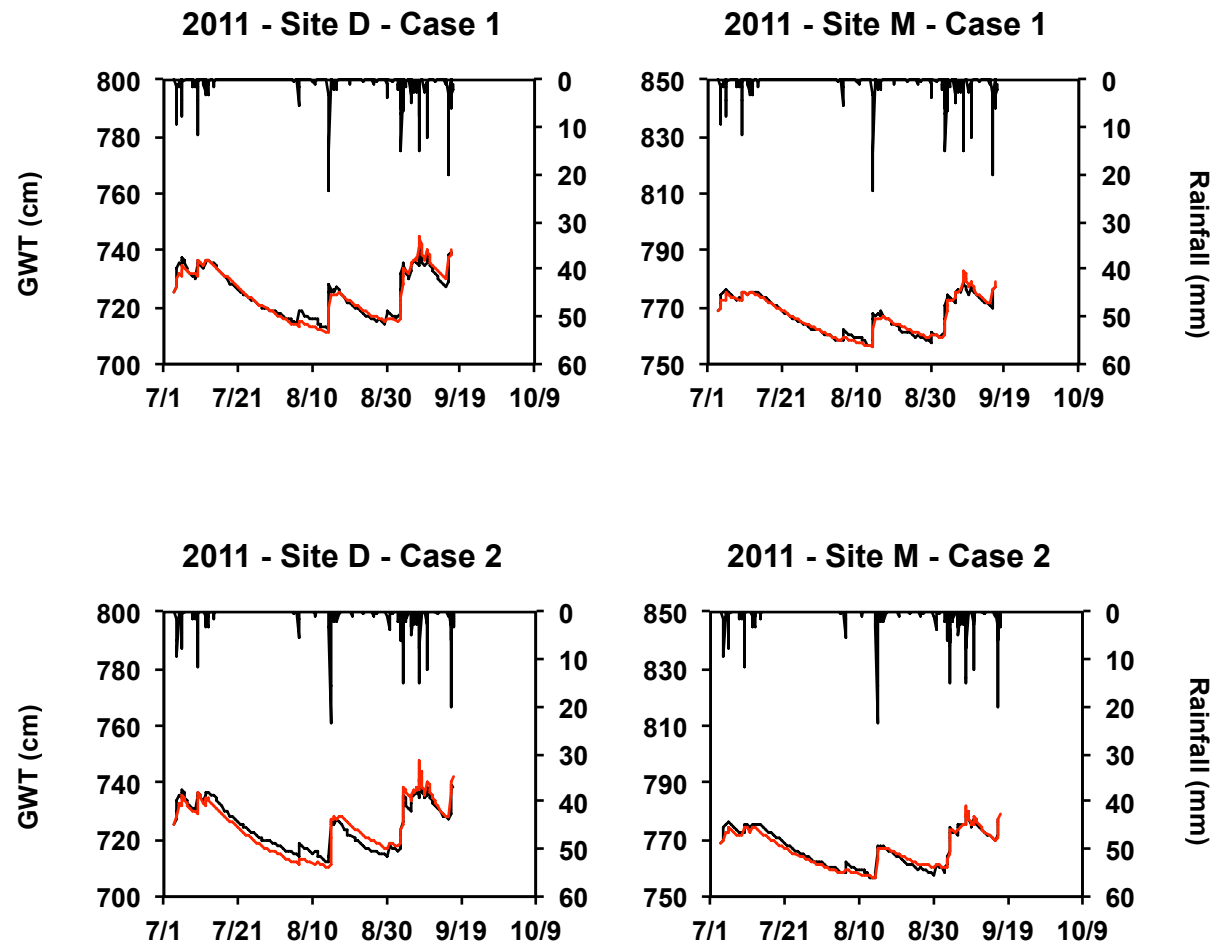


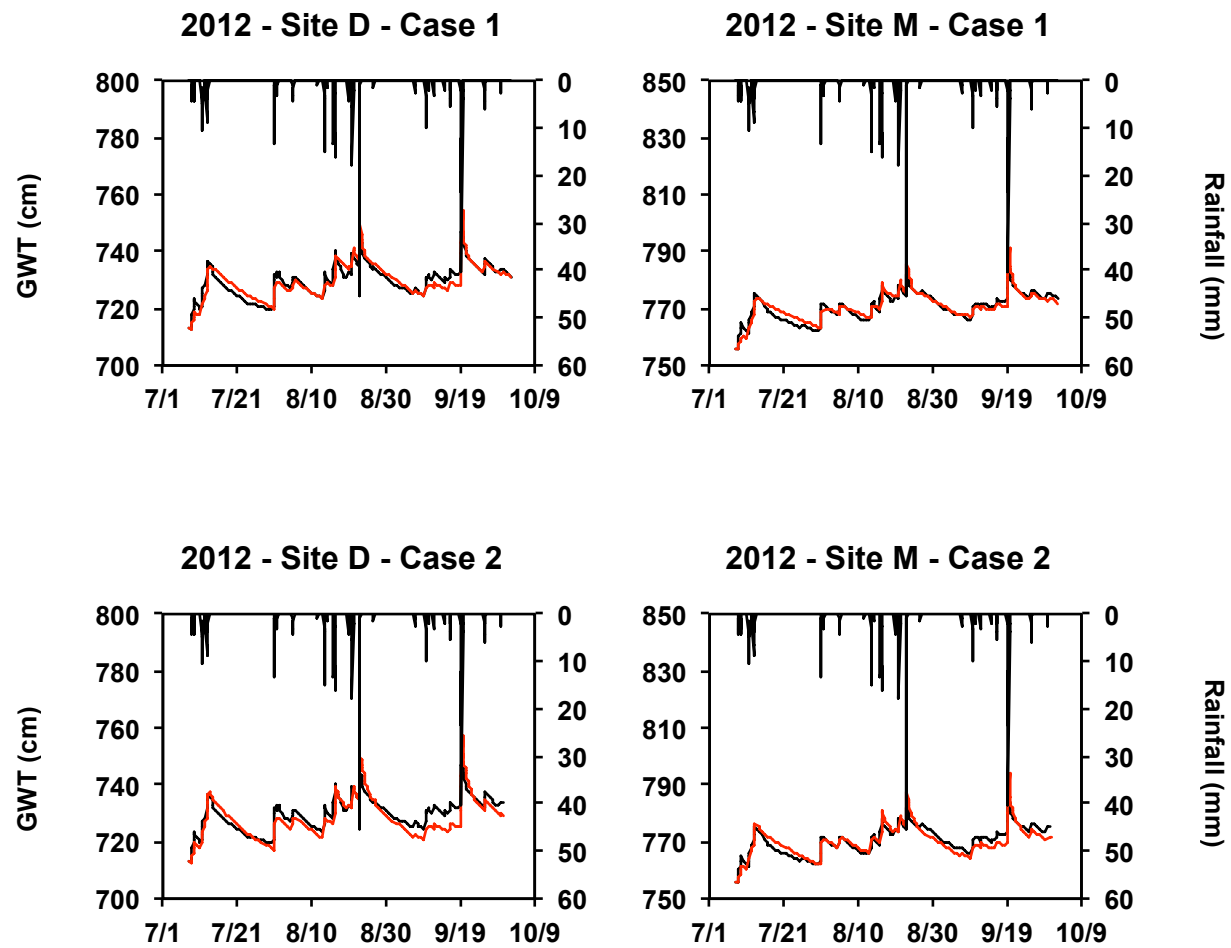






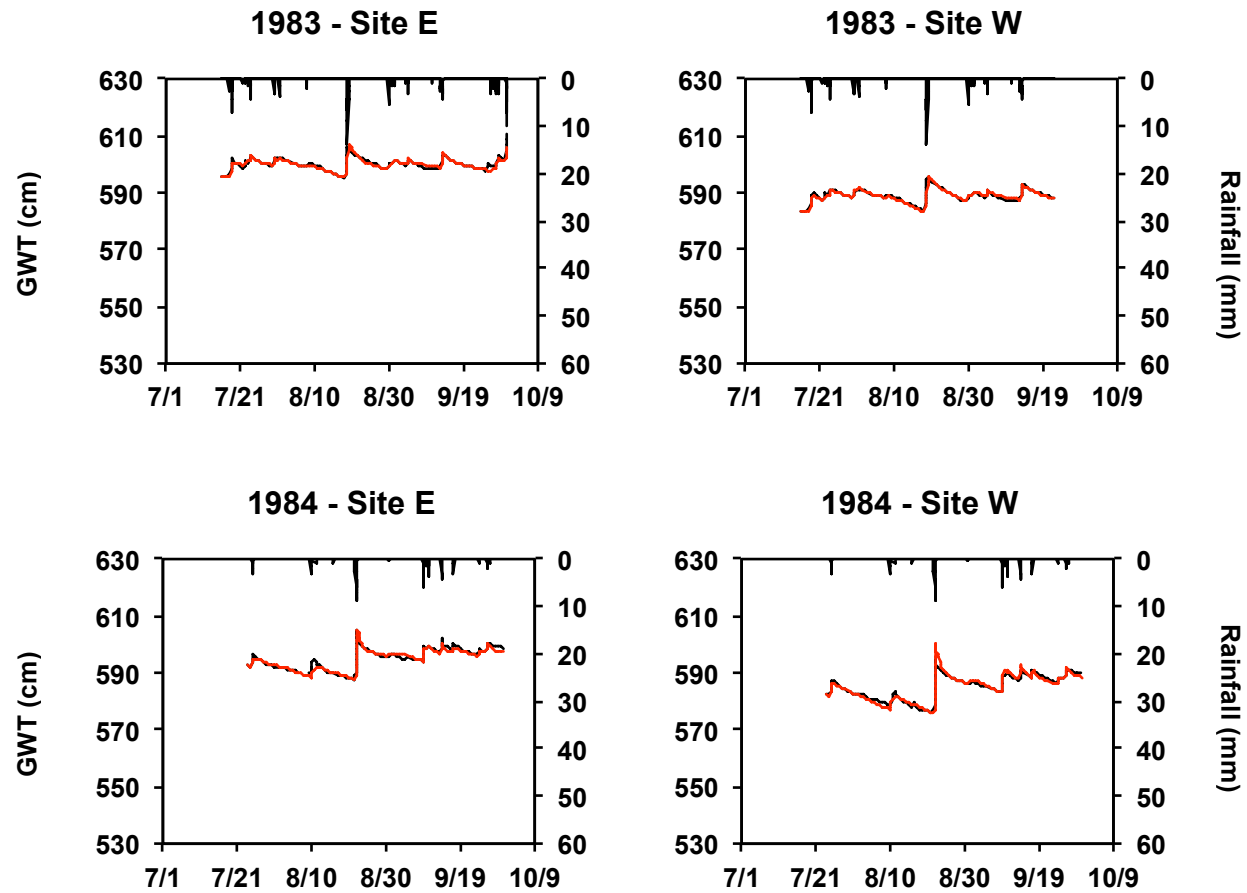


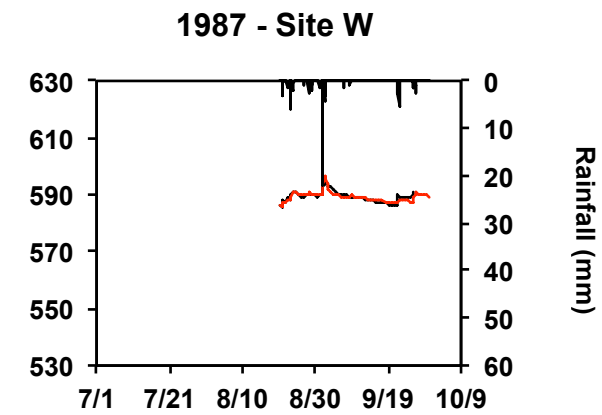
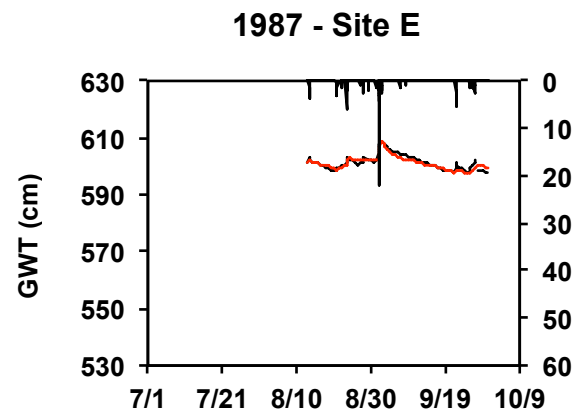
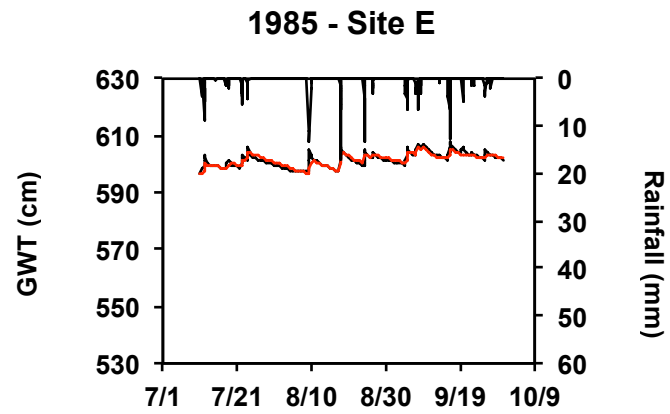




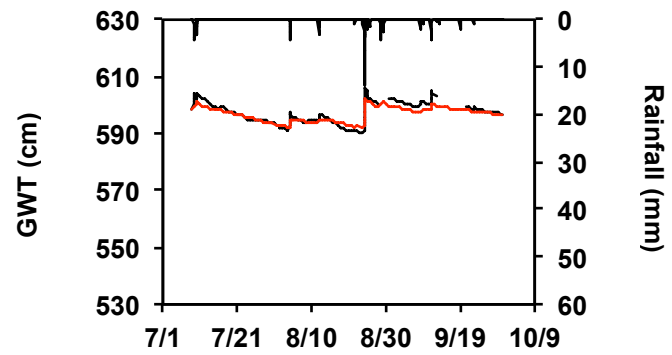
APPENDIX FIGURES

Figure 3. The optimum simulation results of Gensekaen, Sarobestu Mire by modified PTM

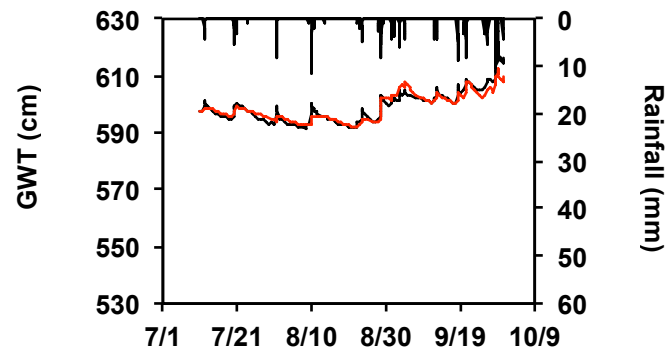


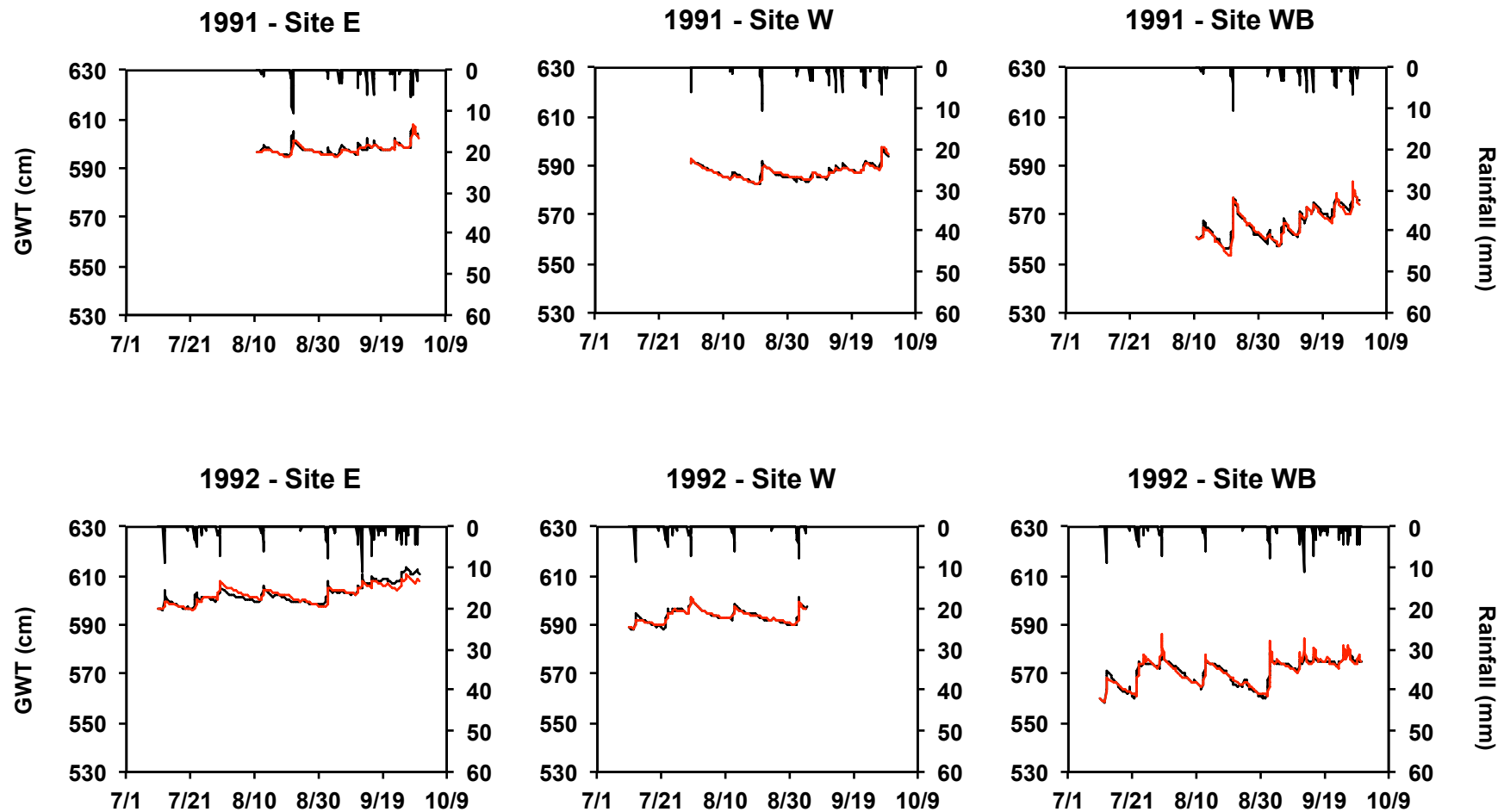


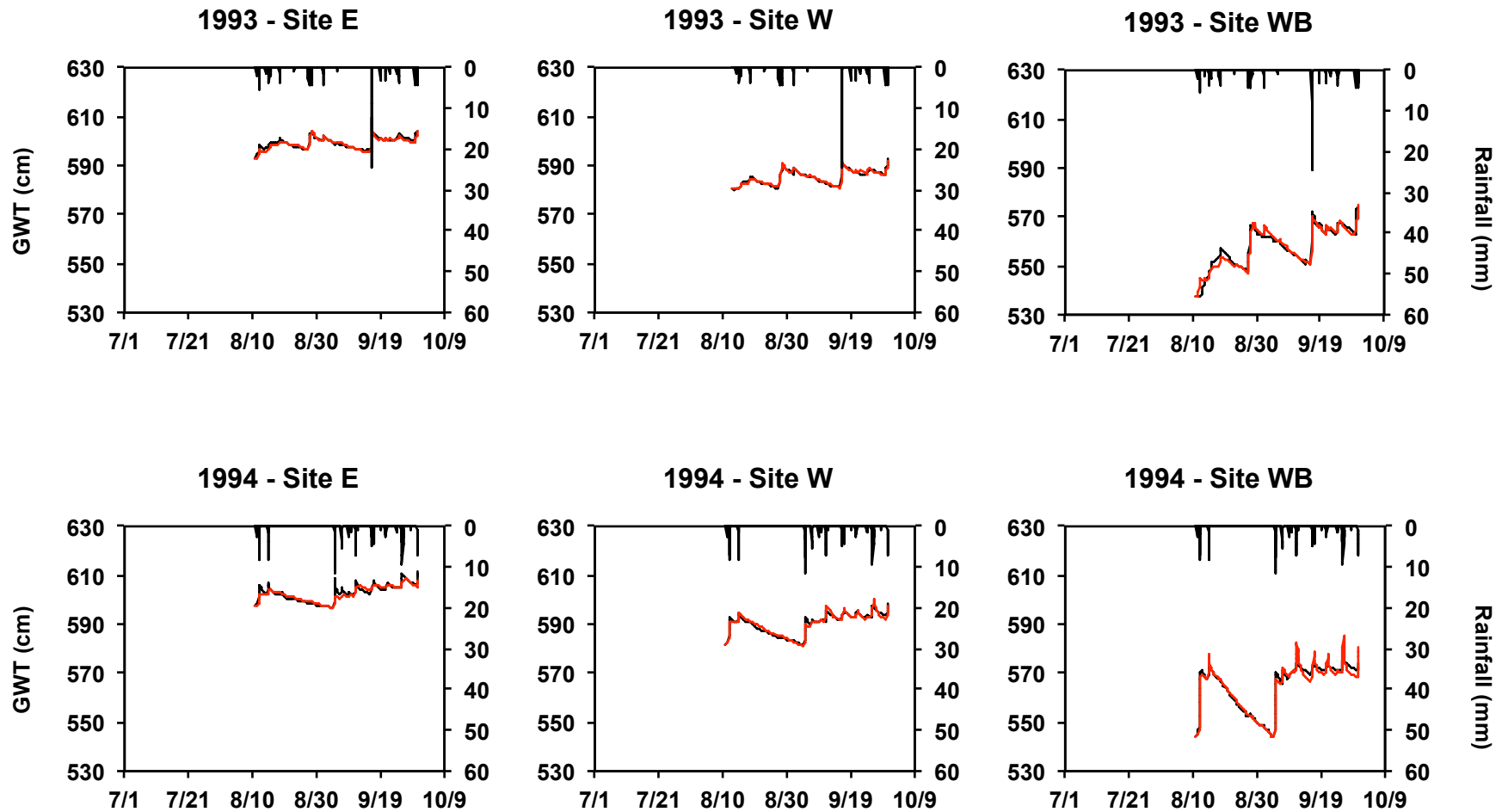
1988 - Site E

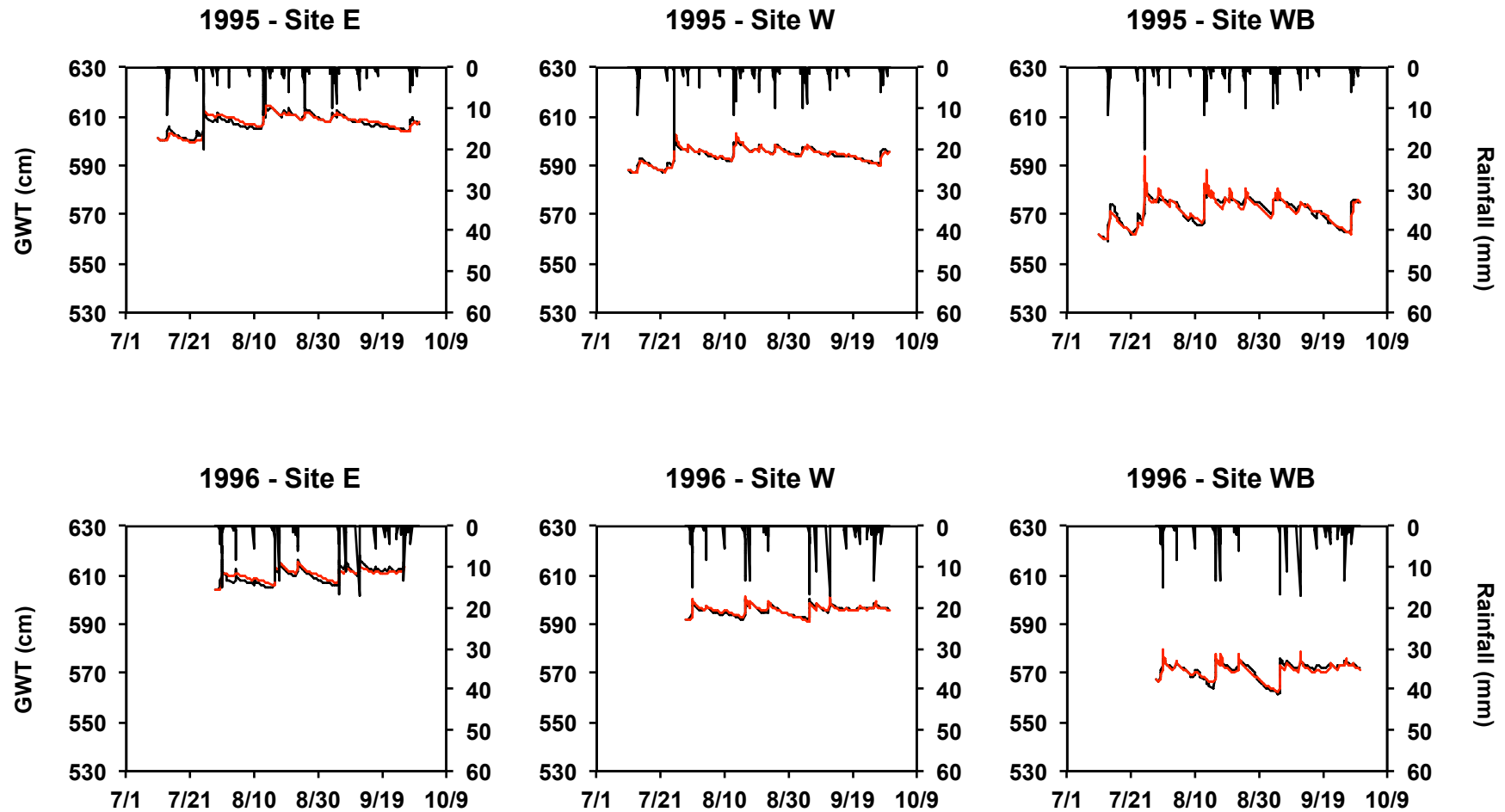


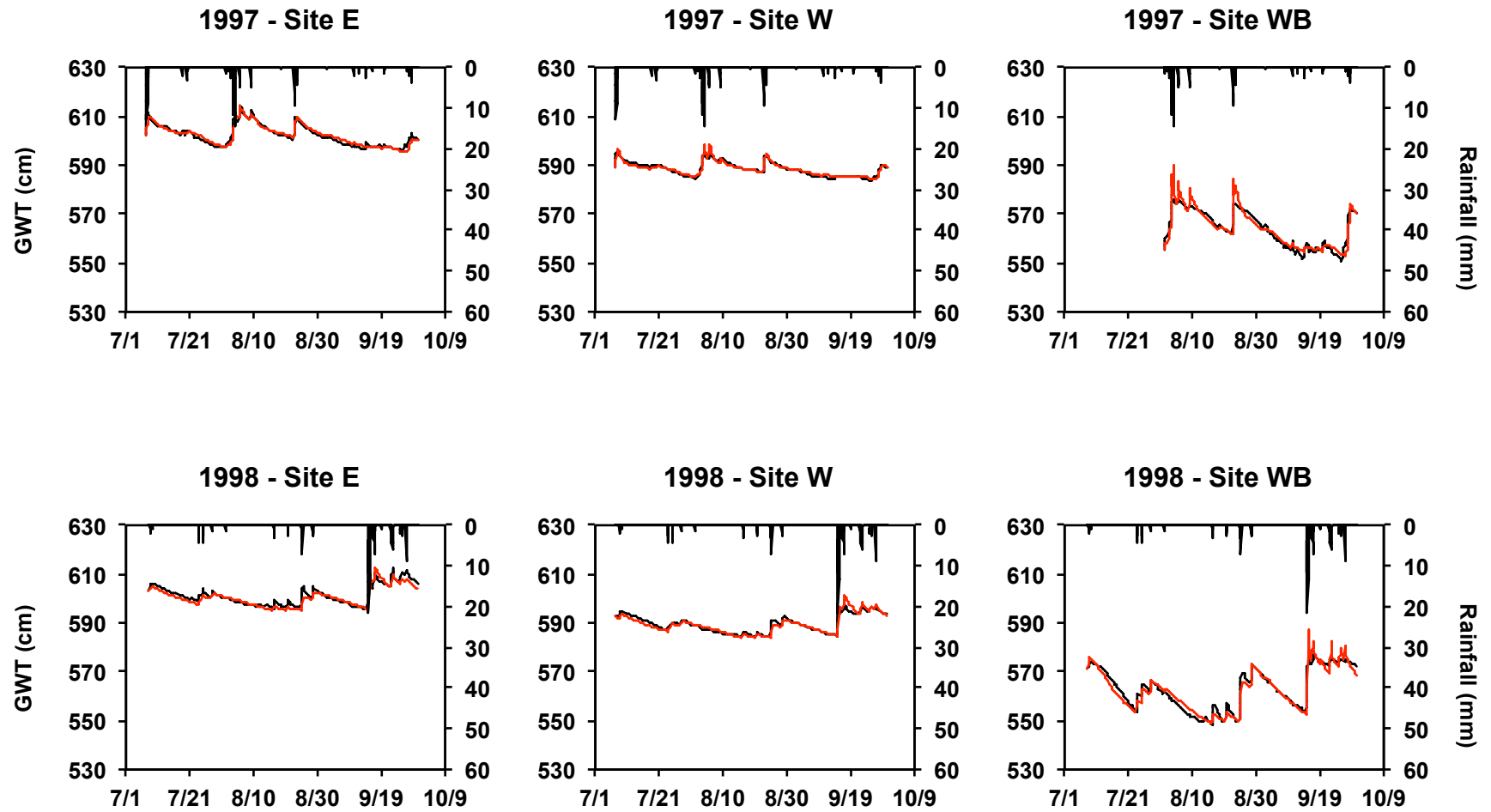
1989 - Site E

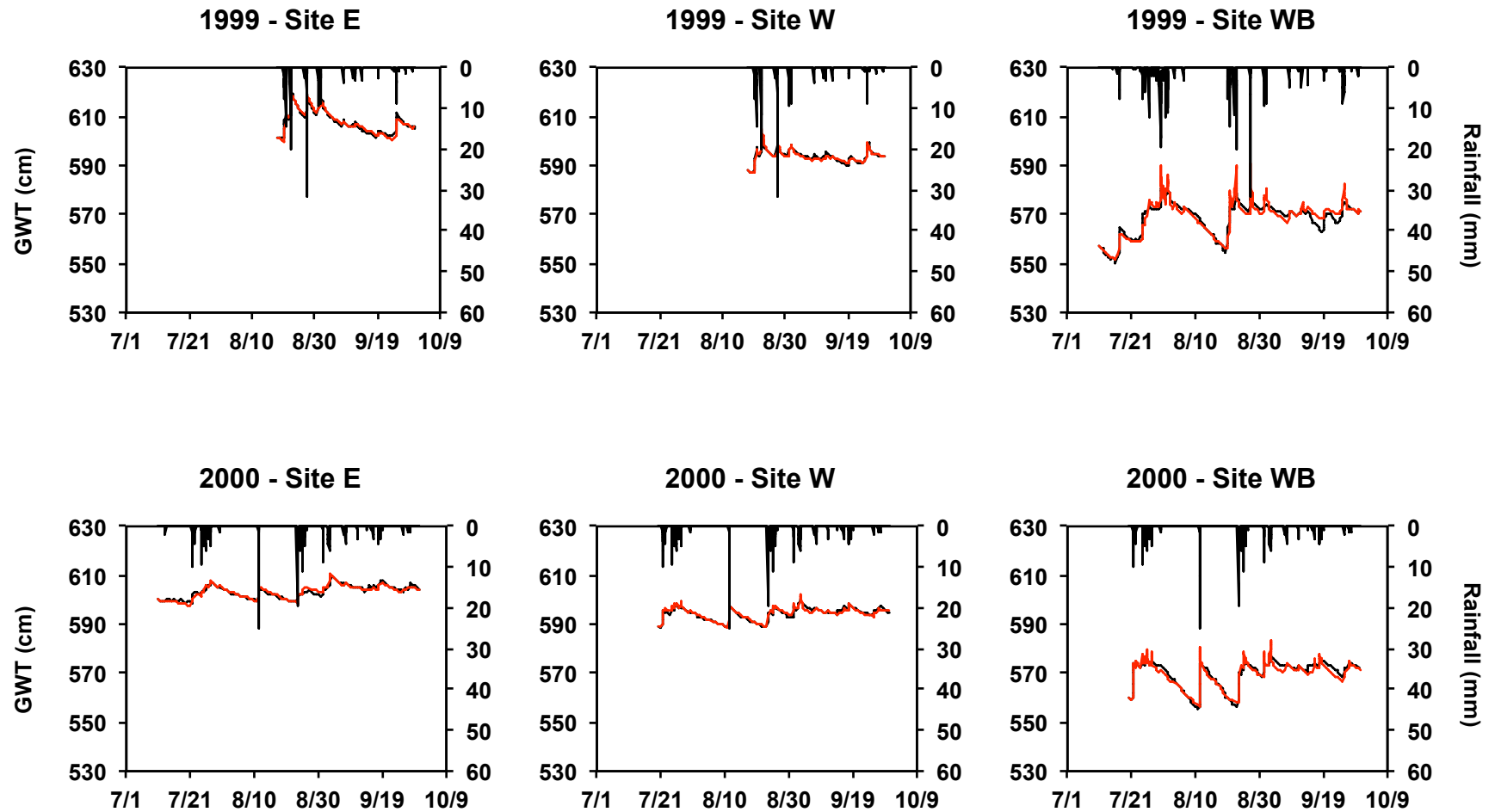


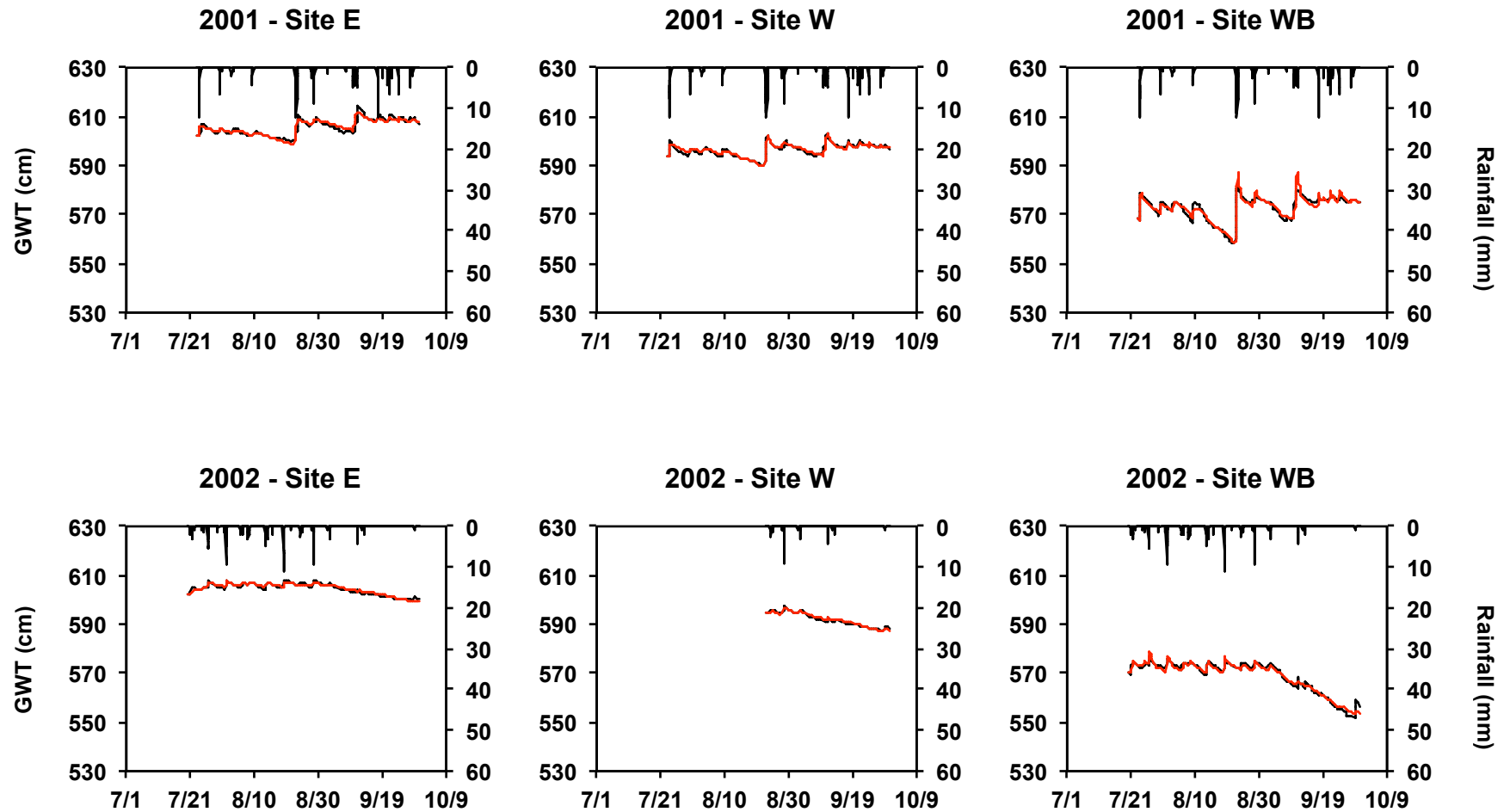


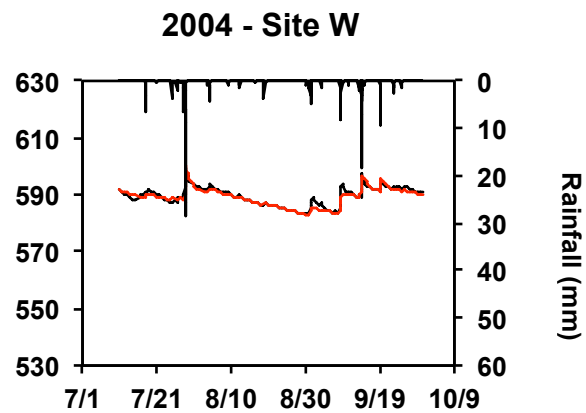
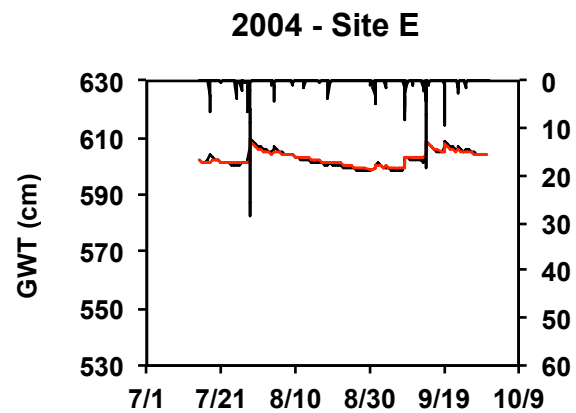
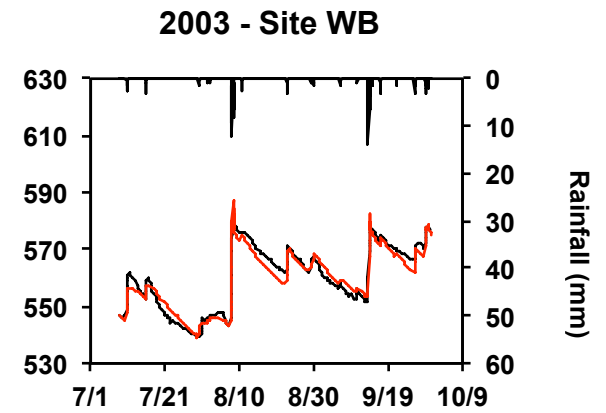
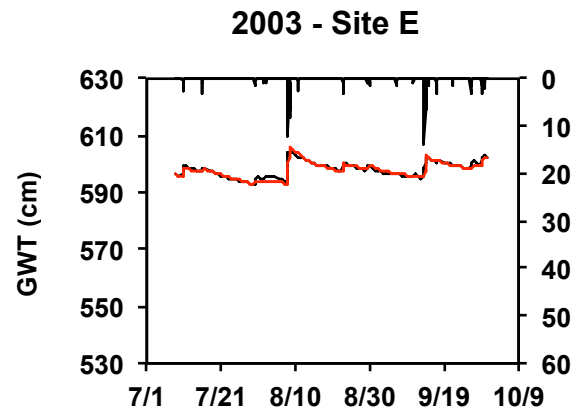




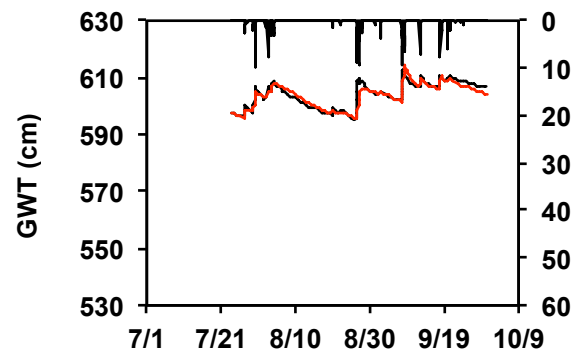




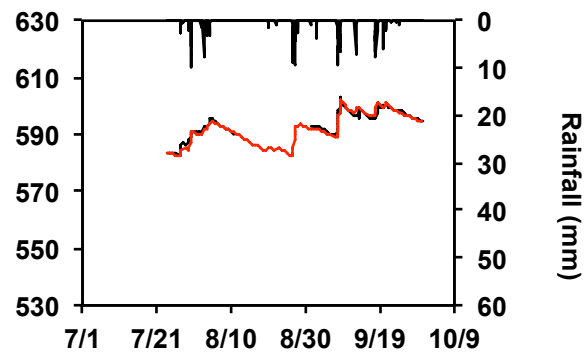




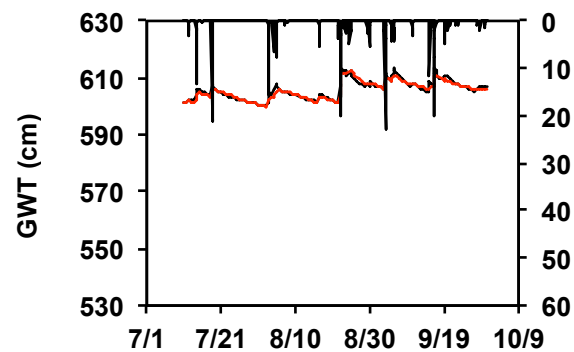
2005 - Site E



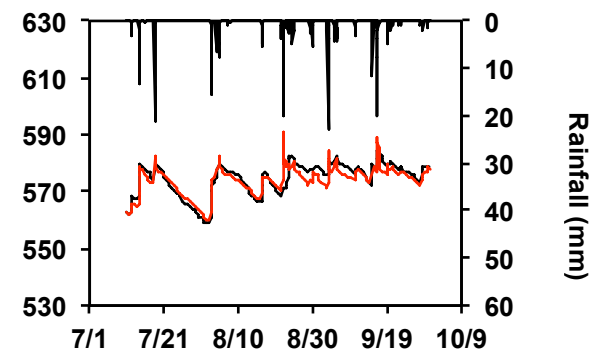
2005 - Site W

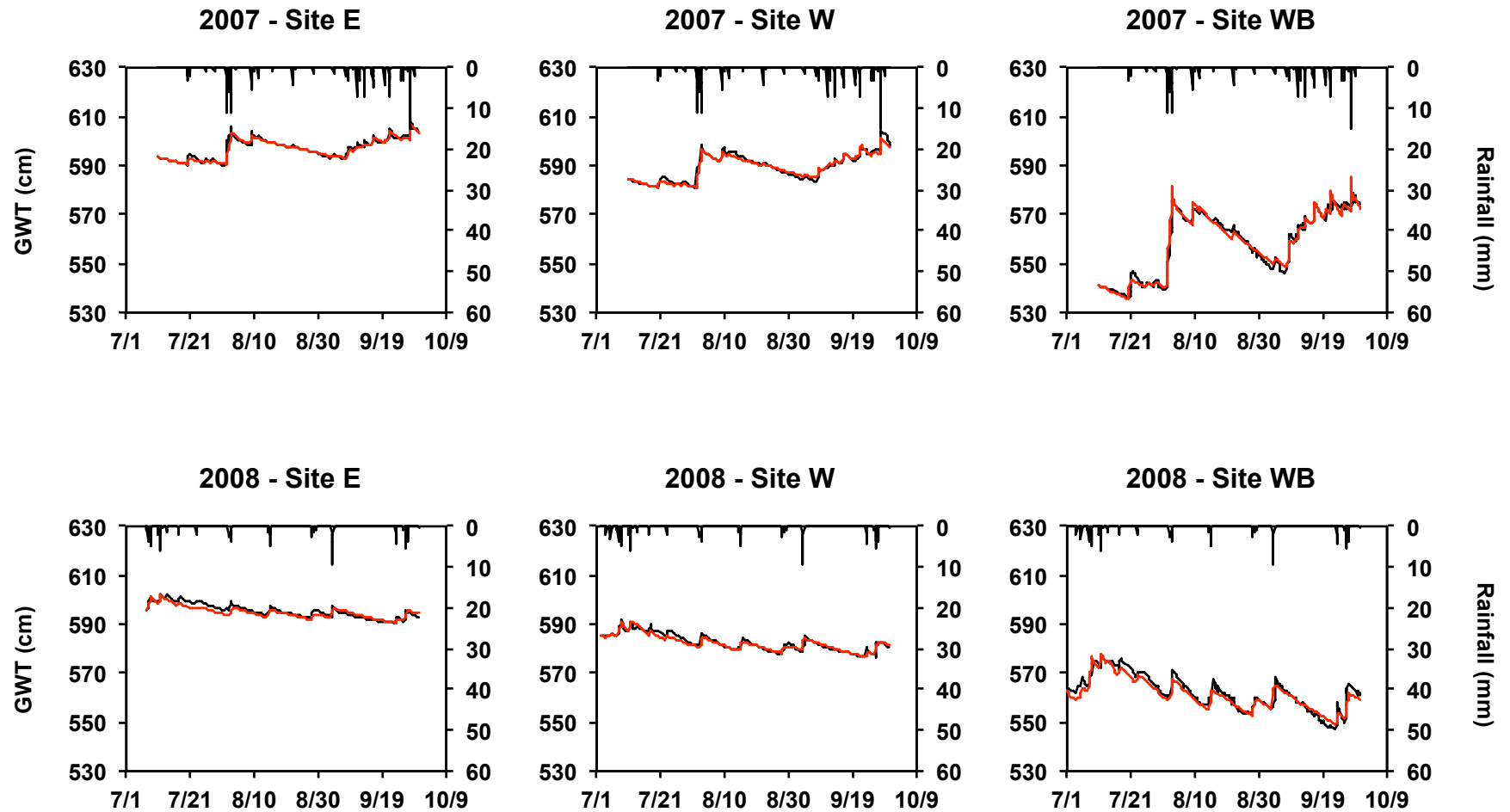


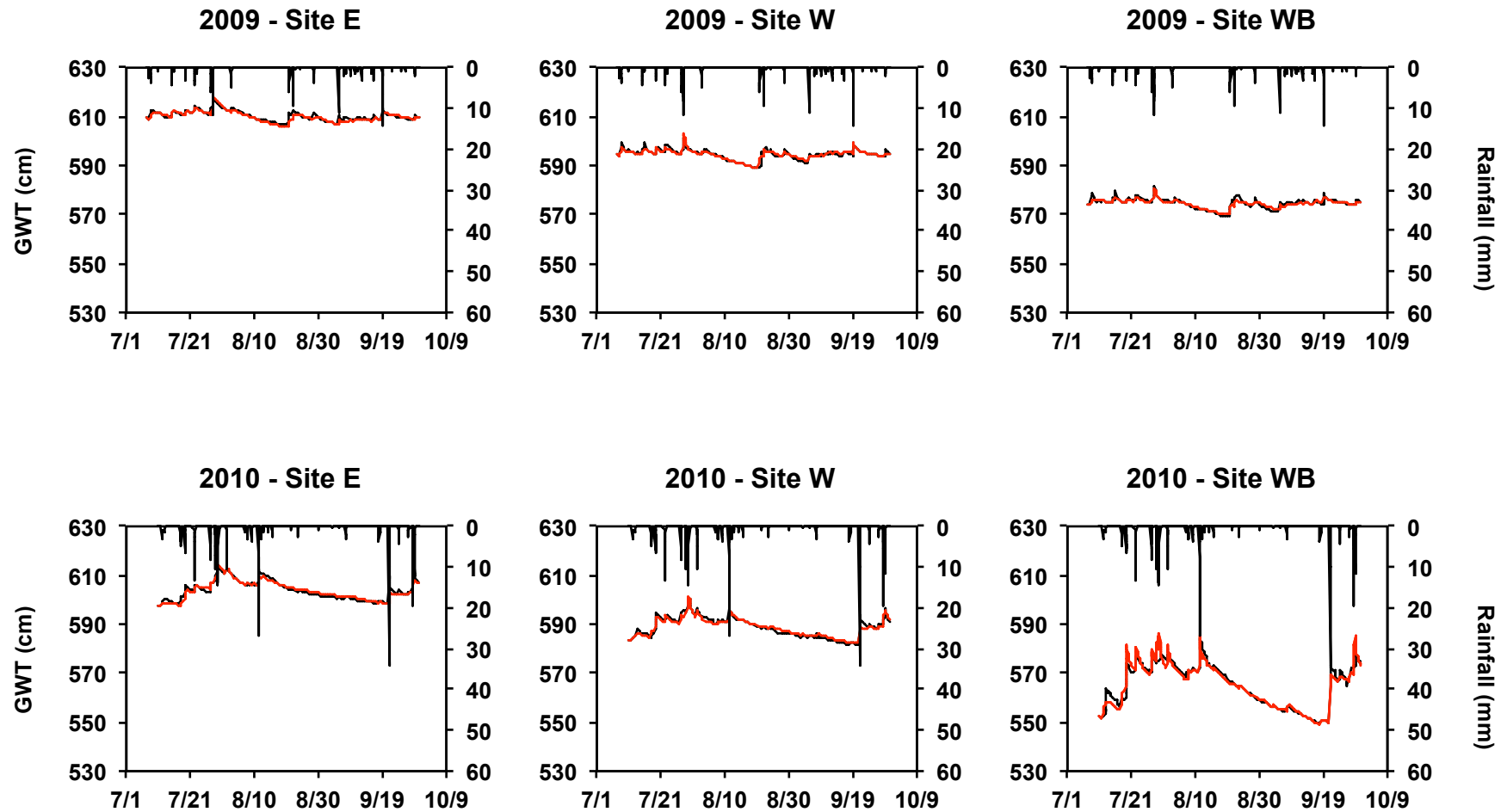
2006 - SiteE

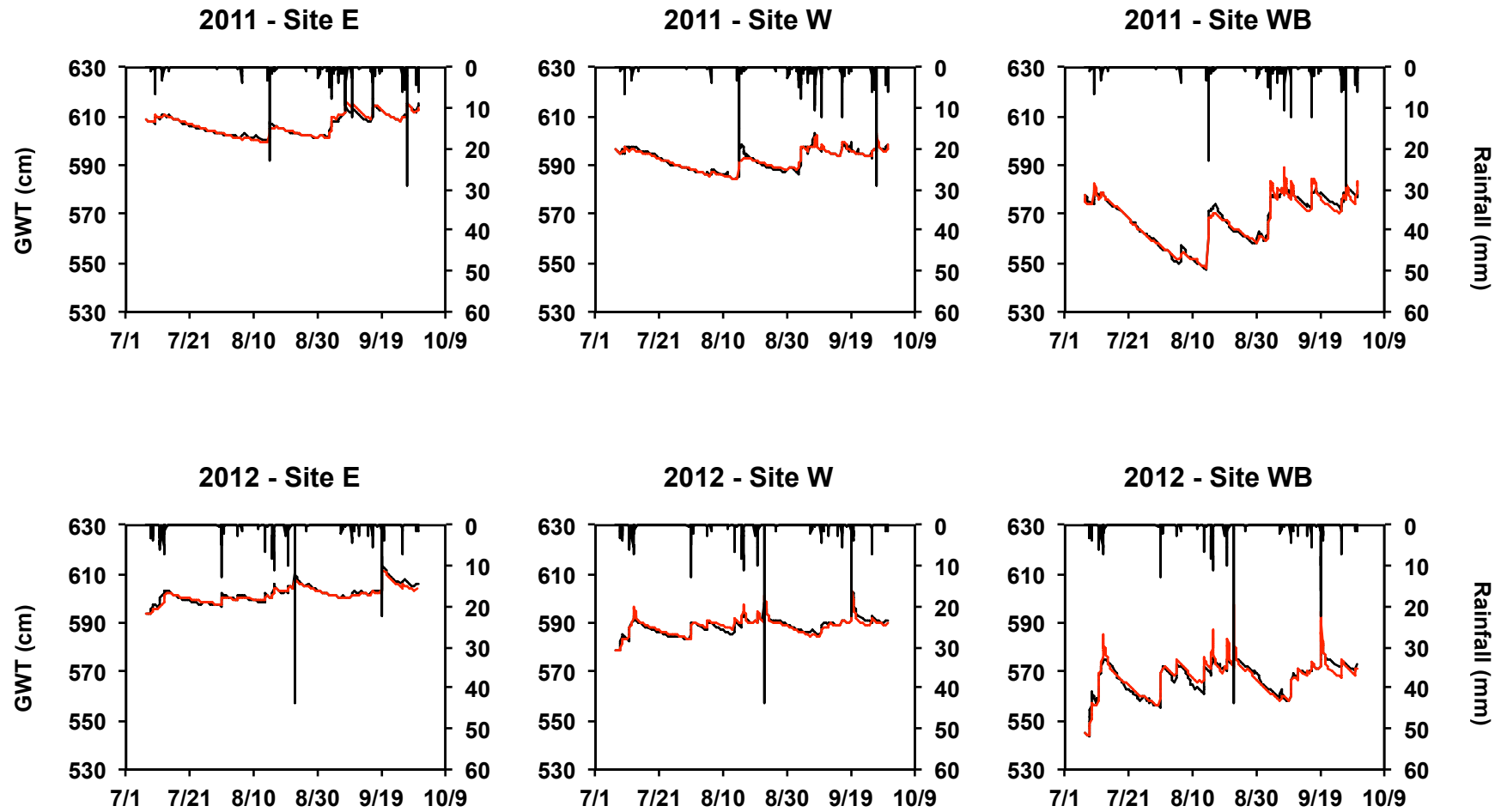


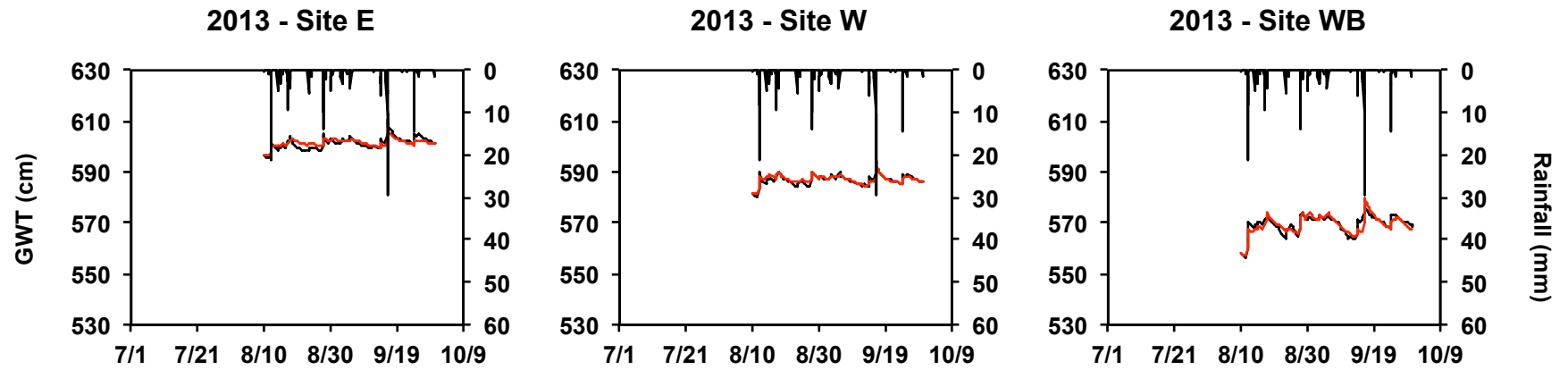
2006 - Site WB











Original Peatland Tank Model's Macro module in Microsoft Excel

```
Sub TANQMODEL2013()
```

```
Worksheets.Select
```

```
Selection.Cells.Clear
```

```
'ファイルの読み込み
```

```
Dim 雨量 As String
```

```
雨量 = InputBox("計算を行うファイルの名前を保存場所から入力してください。", "open  
file", "Macintosh HD:Users:tochikairyogakukenyuushitsu:Desktop:tanqmodel:1999wb.xls")
```

```
Workbooks.Open filename:=雨量
```

```
Worksheets("sheet1").Range("A:D").Copy
```

```
Windows("TANQMODEL-1h2013.xls").Activate
```

```
Range("A1").Select
```

```
ActiveCell.Cells.Select
```

```
ActiveSheet.Paste
```

```
Close
```

```
'計算期間の設定
```

```
Do
```

```
Dim SM, SD, S, FM, FD, F, ss, ff, Yyear As Integer
```

```
SMline:
```

```
SM = InputBox("計算を始める月は", "計算期間の入力", "7")
```

```
If SM = "" Then GoTo Endline
```

```
SDline:
```

```
SD = InputBox("計算を始める日は", "計算期間の入力", "11")
```

```
If SD = "" Then GoTo SMline
```

```
FMline:
```

```
FM = InputBox("計算を終わる月は", "計算期間の入力", "9")
```

```
If FM = "" Then GoTo SDline
```

```
FDline:
```

```
FD = InputBox("計算を終わる日は", "計算期間の入力", "30")
```

```
If FD = "" Then GoTo FMline
```

Cells(3, 4) = SM & "/" & SD & "～" & FM & "/" & FD

Yyear = Year(Cells(13, 1))

If (Yyear / 4) - Int(Yyear / 4) = 0 Then '閏年のとき

Select Case SM

Case 1

S = 13

Case 2

S = 757

Case 3

S = 1453

Case 4

S = 2197

Case 5

S = 2917

Case 6

S = 3661

Case 7

S = 4381

Case 8

S = 5125

Case 9

S = 5869

Case 10

S = 6589

Case 11

S = 7333

Case 12

S = 8053

End Select

End If

If (Yyear / 4) - Int(Yyear / 4) > 0 Then '閏年でないとき

Select Case SM

Case 1

S = 13

Case 2

S = 757

Case 3

S = 1429

Case 4

S = 2173

Case 5

S = 2893

Case 6

S = 3637

Case 7

S = 4357

Case 8

S = 5101

Case 9

S = 5845

Case 10

S = 6565

Case 11

S = 7309

Case 12

S = 8029

End Select

End If

ss = S + 24 * (SD - 1)

If (Yyear / 4) - Int(Yyear / 4) = 0 Then '閏年のとき

Select Case FM

Case 1

F = 13

Case 2

F = 757

Case 3

F = 1453

Case 4

F = 2197

Case 5

F = 2917

Case 6

F = 3661

Case 7

F = 4381

Case 8

F = 5125

Case 9

F = 5869

Case 10

F = 6589

Case 11

F = 7333

Case 12

F = 8053

End Select

End If

If (Yyear / 4) - Int(Yyear / 4) > 0 Then '閏年でないとき

Select Case FM

Case 1

F = 13

Case 2

F = 757

Case 3

F = 1429

```
Case 4
F = 2173
Case 5
F = 2893
Case 6
F = 3637
Case 7
F = 4357
Case 8
F = 5101
Case 9
F = 5845
Case 10
F = 6565
Case 11
F = 7309
Case 12
F = 8029
End Select
End If
ff = F + 24 * FD
```

'初期値及び各係数の設定

Dim R, GA, A1, A2, A3, HA1, HA2, HA3, C, QA1, QA2, QA3 As Integer

A1line:

A1 = InputBox("A1", "A1", "0.0013")

If A1 = "" Then GoTo FDline

A2line:

A2 = InputBox("A2", "A2", "0.03")

If A2 = "" Then GoTo A1line

A3line:

A3 = 1

HA2line:

HA2 = 606

RangeA = "A" & ss

RangeB = "C" & ff

Range(RangeA & ":" & RangeB).Select

ActiveWorkbook.Worksheets("Sheet1").Sort.SortFields.Clear

ActiveWorkbook.Worksheets("Sheet1").Sort.SortFields.Add Key:=Range(RangeB), _
SortOn:=xlSortOnValues, Order:=xlDescending, DataOption:=xlSortNormal

With ActiveWorkbook.Worksheets("Sheet1").Sort

.SetRange Range(RangeA & ":" & RangeB)

.Header = xlNo

.MatchCase = False

.Orientation = xlTopToBottom

.SortMethod = xlPinYin

.Apply

End With

inta = Val(Format(((ff - ss + 1) / 3), "0")) + ss

HA2 = Val(Format(Range("C" & inta).Value, "0.00"))

ActiveWorkbook.Worksheets("Sheet1").Sort.SortFields.Clear

ActiveWorkbook.Worksheets("Sheet1").Sort.SortFields.Add Key:=Range(RangeA), _
SortOn:=xlSortOnValues, Order:=xlAscending, DataOption:=xlSortNormal

With ActiveWorkbook.Worksheets("Sheet1").Sort

.SetRange Range(RangeA & ":" & RangeB)

.Header = xlGuess

.MatchCase = False

.Orientation = xlTopToBottom

.SortMethod = xlPinYin

.Apply

End With

HA2 = InputBox("HA2", "HA2", HA2)

If HA2 = "" Then GoTo A3line

HA1 = HA2 - 40

HA3 = HA2 + 10

C = InputBox("C", "A1", "3")

'タンクモデルの計算

GA = Cells(ss, 3) '初期タンク水位の設定（実測値）

Cells(ss, 6) = GA

For I = ss To ff

R = Cells(I, 4) * 0.1

CR = C * R

QA1 = A1 * (GA - HA1)

QA2 = A2 * (GA - HA2)

QA3 = A3 * (GA - HA3)

If (GA - HA1) <= 0 Then

QA1 = 0

End If

If (GA - HA2) <= 0 Then

QA2 = 0

End If

If (GA - HA3) <= 0 Then

QA3 = 0

End If

Cells(I + 1, 7) = QA1 * 10

Cells(I + 1, 8) = QA2 * 10

Cells(I + 1, 9) = QA3 * 10

Cells(I + 1, 10) = (Cells(I + 1, 7) + Cells(I + 1, 8) + Cells(I + 1, 9)) / C

GA = GA + CR - QA1 - QA2 - QA3

Cells(I + 1, 6) = GA

Next I

Cells(5, 6) = "A1=" & A1

Cells(6, 6) = "A2=" & A2

Cells(7, 6) = "A3=" & A3

Cells(8, 6) = "HA1=" & HA1

Cells(9, 6) = "HA2=" & HA2

Cells(10, 6) = "HA3=" & HA3

Cells(11, 6) = "C=" & C

Cells(12, 6) = "計算値"

Cells(12, 3) = "実測値"

Cells(12, 4) = "降水量"

Cells(12, 7) = "QA1"

Cells(12, 8) = "QA2"

Cells(12, 9) = "QA3"

Cells(12, 10) = "損失流出高"

'相関係数 R の値を求める

Range("F1").Value = "=correl(C" & ss & ":C" & ff & ",F" & ss & ":F" & ff & ") "

'グラフの作成

Range("A15").Select

Dim Arange, Crange, Frange As String

Arange = "A" & ss & ":" & "A" & ff

Crange = "C" & ss & ":" & "C" & ff

Frange = "F" & ss & ":" & "F" & ff

If (Yyear / 4) - Int(Yyear / 4) = 0 Then 'うるう年

Charts.Add

ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

ActiveChart.SetSourceData Source:=Sheets("Sheet1").Range("D5")

ActiveChart.SeriesCollection.NewSeries

ActiveChart.SeriesCollection.NewSeries

```

ActiveChart.SeriesCollection(1).XValues = Worksheets("Sheet1").Range(Arange)
ActiveChart.SeriesCollection(1).Values = Worksheets("Sheet1").Range(Crange)
ActiveChart.SeriesCollection(1).Name = """"実測""""
ActiveChart.SeriesCollection(2).XValues = Worksheets("Sheet1").Range(Arange)
ActiveChart.SeriesCollection(2).Values = Worksheets("Sheet1").Range(Frange)
ActiveChart.SeriesCollection(2).Name = """"計算値""""
ActiveChart.Location Where:=xlLocationAsObject, Name:="Sheet1"
End If

```

If (Yyear / 4) - Int(Yyear / 4) > 0 Then 'うるう年でない年

```

Charts.Add
ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

```

```

ActiveChart.SetSourceData Source:=Sheets("Sheet1").Range("D5")
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection.NewSeries

```

```

ActiveChart.SeriesCollection(1).XValues = Worksheets("Sheet1").Range(Arange)
ActiveChart.SeriesCollection(1).Values = Worksheets("Sheet1").Range(Crange)
ActiveChart.SeriesCollection(1).Name = """"実測""""
ActiveChart.SeriesCollection(2).XValues = Worksheets("Sheet1").Range(Arange)
ActiveChart.SeriesCollection(2).Values = Worksheets("Sheet1").Range(Frange)
ActiveChart.SeriesCollection(2).Name = """"計算値""""
ActiveChart.Location Where:=xlLocationAsObject, Name:="Sheet1"
End If

```

```

With ActiveChart
    .HasTitle = True
    .ChartTitle.Characters.Text = "計算値との比較"
    .Axes(xlCategory, xlPrimary).HasTitle = True
    .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "日付"
    .Axes(xlValue, xlPrimary).HasTitle = True

```

```

        .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "地下水位(cm)"
    End With
    ActiveChart.PlotArea.Select
    With Selection.Interior
        .ColorIndex = 2
        .PatternColorIndex = 1
        .Pattern = xlSolid
    End With

    ActiveChart.ShowWindow = True

    For j = 1 To ActiveSheet.ChartObjects.Count          '表操作
        ActiveSheet.ChartObjects(j).Left = 50
        ActiveSheet.ChartObjects(j).Top = 180
        ActiveSheet.ChartObjects(j).Width = 850
        ActiveSheet.ChartObjects(j).Height = 400
    Next j
    ActiveWindow.WindowState = xlMaximized
    '確認
    kakunin = MsgBox("このグラフでいい？", Buttons:=vbYesNo, Title:="確認")
    If kakunin = 6 Then
        ActiveChart.ShowWindow = False
        Exit Do
    End If
    If kakunin = 7 Then
        Worksheets("Sheet1").Range("F:F").ClearContents
        ActiveChart.ShowWindow = False
        ActiveChart.ChartArea.Select
        ActiveWindow.Visible = False
        ' Selection.Delete
    End If
Loop
'ファイルの保存

```

```
Dim filename As String
filename = InputBox("保存名を保存場所まで入力してください", "save file", "Macintosh
HD:Users:inoue takashi:Desktop:1h 2010result-A.xls")
If filename <> "" Then
    ActiveWorkbook.SaveAs filename:=filename, FileFormat:=xlWorkbookNormal,
CreateBackup:=False
End If

Endline:
End Sub
```

Modified Peatland Tank Model's Macro module in Microsoft Excel

Sub TANQMODEL2014()

'This macro calculate the groundwater level by rainfall and evapotranspiration interval of 1hour.

'計算期間の設定

Dim SM, SD, S, FM, FD, F, ss, ff, Yyear As Integer

SM = InputBox("計算を始める月は？", "計算期間の入力", "")

SD = InputBox("計算を始める日は？", "計算期間の入力", "")

FM = InputBox("計算を終わる月は？", "計算期間の入力", "")

FD = InputBox("計算を終わる日は？", "計算期間の入力", "")

Cells(3, 4) = SM & "/" & SD & "~" & FM & "/" & FD

Yyear = Year(Cells(13, 1))

If (Yyear / 4) - Int(Yyear / 4) = 0 Then

Select Case SM

Case 1

S = 13

Case 2

S = 757

Case 3

S = 1453

Case 4

S = 2197

Case 5

S = 2917

Case 6

S = 3661

Case 7

S = 4381

Case 8

S = 5125

Case 9

S = 5869

Case 10

S = 6589

Case 11

S = 7333

Case 12

S = 8053

End Select

End If

If (Yyear / 4) - Int(Yyear / 4) > 0 Then

Select Case SM

Case 1

S = 13

Case 2

S = 757

Case 3

S = 1429

Case 4

S = 2173

Case 5

S = 2893

Case 6

S = 3637

Case 7

S = 4357

Case 8

S = 5101

Case 9

S = 5845

Case 10

S = 6565

Case 11

S = 7309

Case 12

S = 8029

End Select

End If

ss = S + 24 * (SD - 1)

If (Yyear / 4) - Int(Yyear / 4) = 0 Then

Select Case FM

Case 1

F = 13

Case 2

F = 757

Case 3

F = 1453

Case 4

F = 2197

Case 5

F = 2917

Case 6

F = 3661

Case 7

F = 4381

Case 8

F = 5125

Case 9

F = 5869

Case 10

F = 6589

Case 11

F = 7333

Case 12

F = 8053

End Select

End If

If (Yyear / 4) - Int(Yyear / 4) > 0 Then

Select Case FM

Case 1

F = 13

Case 2

F = 757

Case 3

F = 1429

Case 4

F = 2173

Case 5

F = 2893

Case 6

F = 3637

Case 7

F = 4357

Case 8

F = 5101

Case 9

F = 5845

Case 10

F = 6565

Case 11

F = 7309

Case 12

F = 8029

End Select

End If

ff = F + 24 * FD

Do

'初期値及び各係数の設定

Dim R, ET, GA, A1, A2, A3, HA1, HA2, HA3, C, QA1, QA2, QA3 As Integer

A1 = InputBox("A1?")

A2 = InputBox("A2?")

A3 = InputBox("A3?")

HA1 = Cells(11, 3)

HA2 = Cells(11, 4)

HA3 = Cells(11, 5)

C = InputBox("C?")

'タンクモデルの計算

GA = Cells(ss, 3) '初期タンク水位の設定（実測値）

Cells(ss, 6) = GA

For I = ss To ff

R = Cells(I + 1, 4) * 0.1

CR = C * R

QA1 = A1 * (GA - HA1)

QA2 = A2 * (GA - HA2)

QA3 = A3 * (GA - HA3)

ET = Cells(I + 1, 5) * 0.1

CET = C * ET

If (GA - HA1) <= 0 Then

QA1 = 0

End If

If (GA - HA2) <= 0 Then

QA2 = 0

End If

If (GA - HA3) <= 0 Then

QA3 = 0

End If

Cells(I + 1, 7) = QA1 * 10

Cells(I + 1, 8) = QA2 * 10

Cells(I + 1, 9) = QA3 * 10

Cells(I + 1, 10) = (Cells(I + 1, 7) + Cells(I + 1, 8) + Cells(I + 1, 9)) / C

GA = GA + CR - QA1 - QA2 - QA3 - CET

Cells(I + 1, 6) = GA

Next I

Cells(5, 6) = "A1=" & A1

Cells(6, 6) = "A2=" & A2

Cells(7, 6) = "A3=" & A3

Cells(8, 6) = "HA1=" & HA1

Cells(9, 6) = "HA2=" & HA2

Cells(10, 6) = "HA3=" & HA3

Cells(11, 6) = "C=" & C

Cells(12, 6) = "計算値"

Cells(12, 3) = "実測値"

Cells(12, 4) = "降水量"

Cells(12, 7) = "QA1"

Cells(12, 8) = "QA2"

Cells(12, 9) = "QA3"

Cells(12, 10) = "損失流出高"

'グラフの作成

Dim Arange, Crange, Frange As String

Arange = "A" & ss & ":" & "A" & ff

Crange = "C" & ss & ":" & "C" & ff

Frange = "F" & ss & ":" & "F" & ff

If (Yyear / 4) - Int(Yyear / 4) = 0 Then

Charts.Add

ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

ActiveChart.SetSourceData Source:=Sheets("Sheet1").Range("D5")

ActiveChart.SeriesCollection.NewSeries

ActiveChart.SeriesCollection.NewSeries

ActiveChart.SeriesCollection(1).XValues = Worksheets("Sheet1").Range(Arange)

ActiveChart.SeriesCollection(1).Values = Worksheets("Sheet1").Range(Crange)

ActiveChart.SeriesCollection(1).Name = """"実測""""

ActiveChart.SeriesCollection(2).XValues = Worksheets("Sheet1").Range(Arange)

ActiveChart.SeriesCollection(2).Values = Worksheets("Sheet1").Range(Frange)

ActiveChart.SeriesCollection(2).Name = """"計算値""""

ActiveChart.Location Where:=xlLocationAsObject, Name:="Sheet1"

End If

If (Yyear / 4) - Int(Yyear / 4) > 0 Then

Charts.Add

ActiveChart.ChartType = xlXYScatterSmoothNoMarkers

ActiveChart.SetSourceData Source:=Sheets("Sheet1").Range("D5")

ActiveChart.SeriesCollection.NewSeries

ActiveChart.SeriesCollection.NewSeries

ActiveChart.SeriesCollection(1).XValues = Worksheets("Sheet1").Range(Arange)

ActiveChart.SeriesCollection(1).Values = Worksheets("Sheet1").Range(Crange)

ActiveChart.SeriesCollection(1).Name = """"実測""""

ActiveChart.SeriesCollection(2).XValues = Worksheets("Sheet1").Range(Arange)

ActiveChart.SeriesCollection(2).Values = Worksheets("Sheet1").Range(Frange)

ActiveChart.SeriesCollection(2).Name = """"計算値""""

ActiveChart.Location Where:=xlLocationAsObject, Name:="Sheet1"

End If

With ActiveChart

.HasTitle = True

.ChartTitle.Characters.Text = "計算値との比較"

.Axes(xlCategory, xlPrimary).HasTitle = True

.Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "日付"

.Axes(xlValue, xlPrimary).HasTitle = True

.Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "地下水位(cm)"

End With

ActiveChart.PlotArea.Select

With Selection.Interior

.ColorIndex = 2

.PatternColorIndex = 1

.Pattern = xlSolid

End With

ActiveChart.ShowWindow = True

With ActiveWindow

.WindowState = xlNormal

.Width = 1000

.Height = 600

End With

'確認

kakunin = MsgBox("このグラフでいい？", Buttons:=vbYesNo, Title:="確認")

If kakunin = 6 Then

ActiveChart.ShowWindow = False

Exit Do

End If

If kakunin = 7 Then

Worksheets("Sheet1").Range("F:F").ClearContents

ActiveChart.ShowWindow = False

ActiveChart.ChartArea.Select

```
ActiveWindow.Visible = False

Selection.Delete

End If

Loop

'ファイルの保存
Dim 保存ファイル名 As String
Filename = InputBox("保存名を保存場所まで入力してください", "save file", "Macintosh
HD:Users:inoue takashi:Desktop:1h 2010result-A.xls")

If Filename <> "" Then

'ActiveWorkbook.SaveAs Filename:=保存ファイル名, FileFormat:=xlWorkbookNormal,
CreateBackup:=fals

End If

End Sub
```