Coping with drought in the central highlands – Vietnam
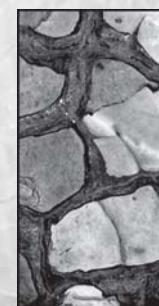
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Coping with drought in the central highlands – Vietnam

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Institute of Environment & Resources
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Vietnam***

Preface

Drought has affected most parts of Vietnam with strong impacts on livelihood and economic development of the country. Since the 1990s it has been of growing concern for the public and media. During the time I have been working on this subject at the Institute of Environment & Resources, DTU, Denmark, some severe drought events occurred in many regions in Vietnam. They got such a high attention from the government and public media that drought issues were one of topics discussed in 10th Vietnamese Communist Party Convention held in Hanoi, April 2006. Thus, drought preparedness and mitigation is essential in Vietnam, especially in the central highlands that has a strong economic development capacity.

This dissertation is composed of a summary, and three papers plus one technical report produced during the last three years. The summary contains an explanation about the development of the works, and the necessary background to understand them. Five sections are included in the summary. Section 1 is an introduction that presents the scope of the research, drought definitions, and the major global patterns of climate variability. Section 2 describes the research region, data, local climate variability, and drought issues in the region. The methods used to develop the papers are displayed in Section 3. A compilation of the results obtained from the three papers and the report is illustrated in Section 4. Section 5 contains a summary and the conclusions of the obtained results. In the appendix the three papers and the report briefly outlined below are included.

- *Nguyen, T. D., Uvo, C. B., and Rosbjerg, D. (2006a):* Relationship between tropical Pacific and Indian Oceans sea surface temperature and monthly precipitation over the central highlands - Vietnam. Revised to *International Journal of Climatology* – **paper I**

Singular value decomposition was used to identify the influence of sea surface temperature in the tropical Pacific and Indian oceans on monthly precipitation over the Vietnamese central highlands. The analysis shows that the influence varies significantly throughout the rainy season and differs between the two oceans.

- *Nguyen, T. D., Uvo, C. B., Rosbjerg, D., and Nguyen, K. Q. (2006b)*: Monthly precipitation forecast for the central highlands - Vietnam. Submitted to *International Journal of Climatology* – **paper II**

The monthly rainfall at selected sites over the central highlands - Vietnam was forecasted using canonical correlation analysis based one monthly sea surface temperature over the tropical Pacific and Indian oceans. The results reveal that the rainfall in April and November at most selected sites can be forecasted from sea surface temperature.

- *Nguyen, T. D., Uvo, C. B., Rosbjerg, D., Nguyen, K. Q., and Nilsson, P. (2006c)*: Using neural networks to forecast rainfall and discharge at early rainy season over the central highlands - Vietnam. Submitted to *Hydrological Sciences Journal* – **paper III**

Non-linear models were used to forecast rainfall and discharge at selected sites over the central highlands - Vietnam in the early rainy season based on both sea surface

temperature in the Pacific Ocean and meteorological data available in the studied region.

- *Nguyen, T. D., Nguyen, K .Q., Uvo, C. B., and Rosbjerg, D.* (2006): Drought: Early warning, mitigation and response in the central highlands - Vietnam. Technical report, 28 pp. – **technical report**

Major components in the context of preparedness and mitigation are presented. Mitigation and response measures to reduce drought impacts on the environmental, economic and social sectors are recommended taking both policy and institutional aspects into account.

The papers are not included in this www-version but may be obtained from the Library at the Institute of Environment & Resources, Bygningtorvet, Building 115, Technical University of Denmark, DK-2800 Kongens Lyngby (library@er.dtu.dk).

Acknowledgements

Abstract

Drought is a natural phenomenon caused by precipitation deficit over a certain period of time over a certain region. It can be observed worldwide affecting broad regions and causing significant damages to human lives as well as economic losses. Drought cannot be prevented but much can be done to reduce the impacts through preparedness and mitigation. Rainfall over the Vietnamese central highlands is mainly generated by the south Asian summer monsoon. Disturbances, however, appear as a result of large-scale circulation phenomena.

Sea surface temperature (SST) is representative of the El Niño-Southern Oscillation (ENSO) phenomenon, which causes worldwide climate variability. The role of the sea surface temperature in both the Pacific and Indian oceans for rainfall variability over the Vietnamese central highlands is investigated in this work by means of singular value decomposition. The particular purpose was to enhance the understanding of the influence of SST on precipitation variability over the Vietnamese central highlands.

Statistical models using canonical correlation analysis have been developed to determine lag time relations between SST and precipitation. Such linear models were used to forecast monthly rainfall throughout the rainy season over the Vietnamese central highlands based on monthly SST in both the Pacific and Indian oceans. Moreover, artificial neural networks (ANN), a non-linear technique, were applied to forecast early rainy season rainfall and discharge at some selected sites over the Vietnamese central highlands based on SST in the Pacific Ocean and some meteorological variables available in the studied region. This technique implied a significant improvement in comparison with the statistically based method.

Drought preparedness and mitigation include active components such as drought definition and monitoring, impact assessment, and a response component. Each component has its own responsibility but the components must be linked closely to enhance the effectiveness of a drought task force. An organizational structure of the components and their responsibilities were proposed, and a drought mitigation and response policy was recommended to enhance the effectiveness of an overall drought task force in Vietnam in general and in the Vietnamese central highlands in particular.

Dansk resumé

Tørke er et naturligt fænomen forårsaget af nedbørsunderskud i et bestemt område gennem et vis tid. Globalt set kan store områder blive berørt med omfattende skader på samfundsøkonomien og menneskers levevilkår og helbred og til følge. Tørke kan ikke forhindres, men forudseenhed og afhjælpende foranstaltninger kan nedbringe skaderne væsentligt. Nedbør i Vietnams centrale højland er i det væsentlige betinget af den sydasiatiske monsun. Der optræder imidlertid forstyrrelser, som kan relateres til stor-skala atmosfæriske fænomener.

Havoverfladetemperaturen i Stillehavet er repræsentativ for det såkaldte El Niño-Southern Oscillation (ENSO) fænomen, som er årsag til globale klimavariationer. I nærværende arbejde er indflydelsen på nedbørsvariabiliteten i Vietnams centrale højland af havoverfladetemperaturen i såvel Stillehavet som det Indiske Ocean undersøgt ved hjælp af ”singular value decomposition” for herigennem at opnå en bedre forståelse af sammenhængen mellem de to fænomener.

På den baggrund er der udviklet lineære prognosticeringsmodeller baseret på ”canonical correlation analysis”, hvor nedbøren i det centrale højland er relateret til havoverfladetemperaturen i oceanerne op til tre måneder bagud i tiden. Med henblik på at opnå en yderligere forbedring blev ikke-lineære modeller i form af ”artificial neural networks” introduceret til prognosticering af nedbøren først og sidst i regntiden baseret på havoverfladetemperaturerne og lokale meteorologiske observationer. Modellerne blev desuden benyttet at prognosticere vandføringen i floderne i tre forskellig oplande i det centrale højland.

Forudseenhed og afhjælpende foranstaltninger af tørke inkluderer en lang række forskellige delkomponenter så som definition af tørke, monitering, vurdering af tørkens omfang og følgevirkninger samt opstilling af modforanstaltninger. Hver komponent er vigtig i sig selv, men alle komponenterne må fungere i et samvirke, hvis der skal opnås en optimal effektivitet af indsatsen. Overordnet må denne styres af en tørke-”task force” på nationalt plan, og det er foreslået, hvorledes den nationale ”task force” og alle underkomponenterne i det centrale højland bør samvirke med henblik på at opnå maksimal effekt.

Abbreviations

a.m.s.l	: Above mean sea level
ANN	: Artificial Neural Network
CCA	: Canonical Correlation Analysis
COADS	: Comprehensive Ocean Atmosphere Data Set
CPCA	: Combined Principle Component Analysis
EEOF	: Extended Empirical Orthogonal Functions
ENSO	: El Niño - Southern Oscillation
EOF	: Empirical Orthogonal Functions
IRI	: International Research Institute for climate and society
ITCZ	: Inter-Tropical Convergence Zone
NAWM	: Northeast Asian Winter Monsoon
NSC	: Normalized Squared Covariance
PCA	: Principle Component Analysis
RMSE	: Root Mean Squared Error
SASM	: South Asian Summer Monsoon
SCS	: South China Sea
SLP	: Sea Level Pressure
SO	: Southern Oscillation
SOI	: Southern Oscillation Index
SPI	: Standardized Precipitation Index
SST	: Sea Surface Temperature
SVD	: Singular Value Decomposition
SWSI	: Surface Water Supply Index
VCH	: Vietnamese Central Highlands

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- *Paper I:* Relationship between tropical Pacific and Indian oceans sea surface temperature and monthly precipitation over the central highlands - Vietnam.

- *Paper II*: Monthly precipitation forecast for the central highlands - Vietnam

- *Paper III*: Using neural networks to forecast rainfall and discharge at early rainy season over the central highlands - Vietnam.

- *Technical report*: Drought: Early warning, mitigation and response in the central highlands - Vietnam.

1. Introduction

1.1 Scope

Drought is considered a worldwide phenomenon affecting broad regions and causing economic losses and significant damage to human lives. It is characterised by a deficit of natural water availability in a region over a certain period of time [*Beran and Rodier 1985*]. Drought differs from aridity, which is characterized by a dry climate with low precipitation and high evaporation losses. Drought characteristics vary significantly from one region to another, e.g., some days without receiving rainfall in a tropical region might be considered a drought occurrence, whereas in dry regions a drought may first be recognised after some years without rain [*Tallaksen and Van Lanen 2003*].

The water demand for human beings, industrial development and agricultural activities has been increasing for the last two decades in developing countries, leading to competition for water that may cause conflicts. So, a prolonged and severe water deficit can potentially cause major environmental, social and economic problems. Overall, drought is considered at least a major natural hazard [*Wilhite 2001*].

The risk associated with drought for any region is assessed by a combination of the regional exposure and the vulnerability of society to the event. The former is associated with natural events, a meteorological drought, e.g., is a result of the occurrence of persistent large-scale disruption or anomalies in the global atmospheric circulation patterns. The latter is determined by social factors such as population, technology, policy, land use, water use, economic development, diversity of economic base and cultural composition. These factors change over time, so that vulnerability will change in response to these changes. Therefore, droughts have temporal effects to different factors due to the changeable vulnerability of such factors in the same region, even if droughts are identical. However, much can be done in order to lessen the impacts of drought on the environmental, economic and social sectors through preparedness and mitigation [*Wilhite et al. 2000*]. Firstly, improved understanding of climatology of a region will significantly provide critical information on historical drought events. Secondly, identifying the factors behind the vulnerability may lead to the development and implementation of various mitigation actions and enable programs to reduce the impacts of future drought events. The components related to preparedness and mitigation aspects are generally presented in Fig. 1.

The main objective of the present study is to highlight measures associated with components of drought preparedness and mitigation over the Vietnamese central highlands. For any drought study, a consistent drought definition is essential and for the formulation of objectives and for a reliable description of the phenomena. Here, meteorological and hydrological droughts are defined in terms of rainfall, discharge,

and a combination of them, and used for analyzing different aspects of droughts such as temporal and spatial scale distribution, as well as for criteria assessment.
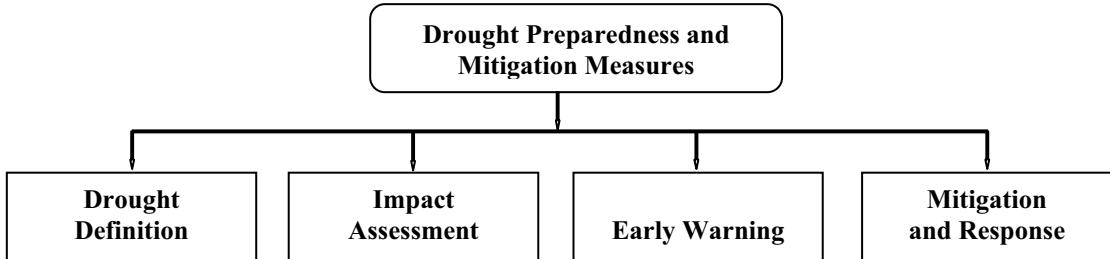
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Figure 1 Drought preparedness and mitigation components (*Wilhite et al. 2000*)

The understanding of the drought phenomenon is enhanced by identifying the causes of droughts and their impacts on the environmental, economic and social sectors. Rainfall and discharge predictions obtained from climate variables such as sea surface temperature are needed to provide valuable information about drought occurrences in advance, and also for understanding the response of droughts to climate variability using drought indicators based on rainfall and discharge. Moreover, drought mitigation, response policy and organizational structures are proposed to implement a drought task force.

1.2 Drought definition

Drought is a normal, recurrent feature of climate and is considered as a worldwide phenomenon affecting broad regions and causing significant damages both in human lives and economic bases [*Wilhite and Glantz 1985*]. *Tallaksen and Van Lanen [2003]* show that drought differs from other natural hazards in several ways as it develops slowly, making its onset and ending difficult to determine, its impacts are extended over a large area and it seldom damages infrastructures. Drought is temporary and its characteristics vary significantly through regions. In general, drought is defined as a persistent occurrence of natural water availability deficit over a certain period in a certain region [*Beran and Rodier 1985*]. The lack of a precise and objective definition of drought is one of main obstacles to drought studies [*Yevjevich 1967*]. Different definitions may lead to different conclusions about the drought phenomenon. However, due to its potential impacts on the environmental and socio-economic sectors, it is essential to define drought in different ways [*Wilhite and Glantz 1985*].

There are two types of drought definitions, namely a conceptual definition and an operational definition. The conceptual definition, held in general terms, makes it easier to understand the drought concept and is essential to establish drought policies. The operational one helps people understanding more details of the drought itself, such as duration, frequency, and severity of droughts in various time scales. *Wilhite and Glantz [1985]* propose a classification of drought definitions based on a disciplinary

perspective using meteorological, agricultural, hydrological and socio-economic drought categories as follow:

A deficit of precipitation over an extended period in a certain region is considered a primary cause for a meteorological drought. It is defined basically on the degree of dryness compared to normal conditions (average amount and duration of dryness), or specifically based on the departure of actual precipitation from the average amount on monthly and seasonal time scales. The meteorological drought definition adheres to one specific region, because the atmospheric condition causing precipitation deficit varies significantly from region to region.

Agricultural drought is expressed by the lack of soil moisture over a certain period of time for a particular crop. This indicates the consequences of a meteorological drought (i.e. lack of precipitation) for a specific crop. The water demand of a crop depends on the prevailing weather conditions, biological characteristics of the specific plant, its growth stage, and the physical and biological properties of the soil. Therefore, a good agricultural drought definition should account for the variable susceptibility of crops during their different development stages, for instance the moisture deficit in the topsoil at planting may decrease plant populations per hectare and reduce the final yield.

Hydrological drought is evidenced by the deficiencies in sub-surface and surface water supplies as a consequence of a meteorological drought. The hydrological drought is usually linked with the effects of a precipitation deficit over an extended period on surface or subsurface water supply. The major points of a drought definition should include the duration, severity, spatial and temporal occurrence, and usually be defined on the watershed or river basin scale. Most droughts are associated with precipitation deficiencies, thus the hydrological drought is generally considered as the final phase in a cycle starting with meteorological and agricultural droughts.

A socio-economic drought is defined as the imbalance between supply and demand in terms of economic goods. It occurs when the demand for economic goods exceeds supply as a result of shortages in water supply due to the natural variability of climate or population growth. It is unlike the drought types mentioned above because its occurrence depends on time and space processes related to the supply and the demand of economic goods. However, the supply of many economic goods, such as water, agricultural production, and hydroelectric power, depends on the natural variability of climate. The increasing demand for economic goods is a result of population growth and growing per capita consumption. So, a future socio-economic drought might be identified by the trends of both supply capacity and demand.

Within the hydrological cycle droughts are comprehensively explained by *Tallaksen and Van Lanen [2003]* (see Fig. 2). The lack of precipitation over a certain period causes a meteorological drought. The shortage of water propagates through the hydrological cycle and combines with high evaporation such that insufficient moisture

in the topsoil may cause an agricultural drought, and subsequently a hydrological drought may develop when groundwater and streamflow are reduced. So, the different types of drought are significantly influenced by each other through the natural hydrological cycle. The hydrological drought is treated as the last pattern recognized in the drought chain, finally showing up when the meteorological drought is ending.
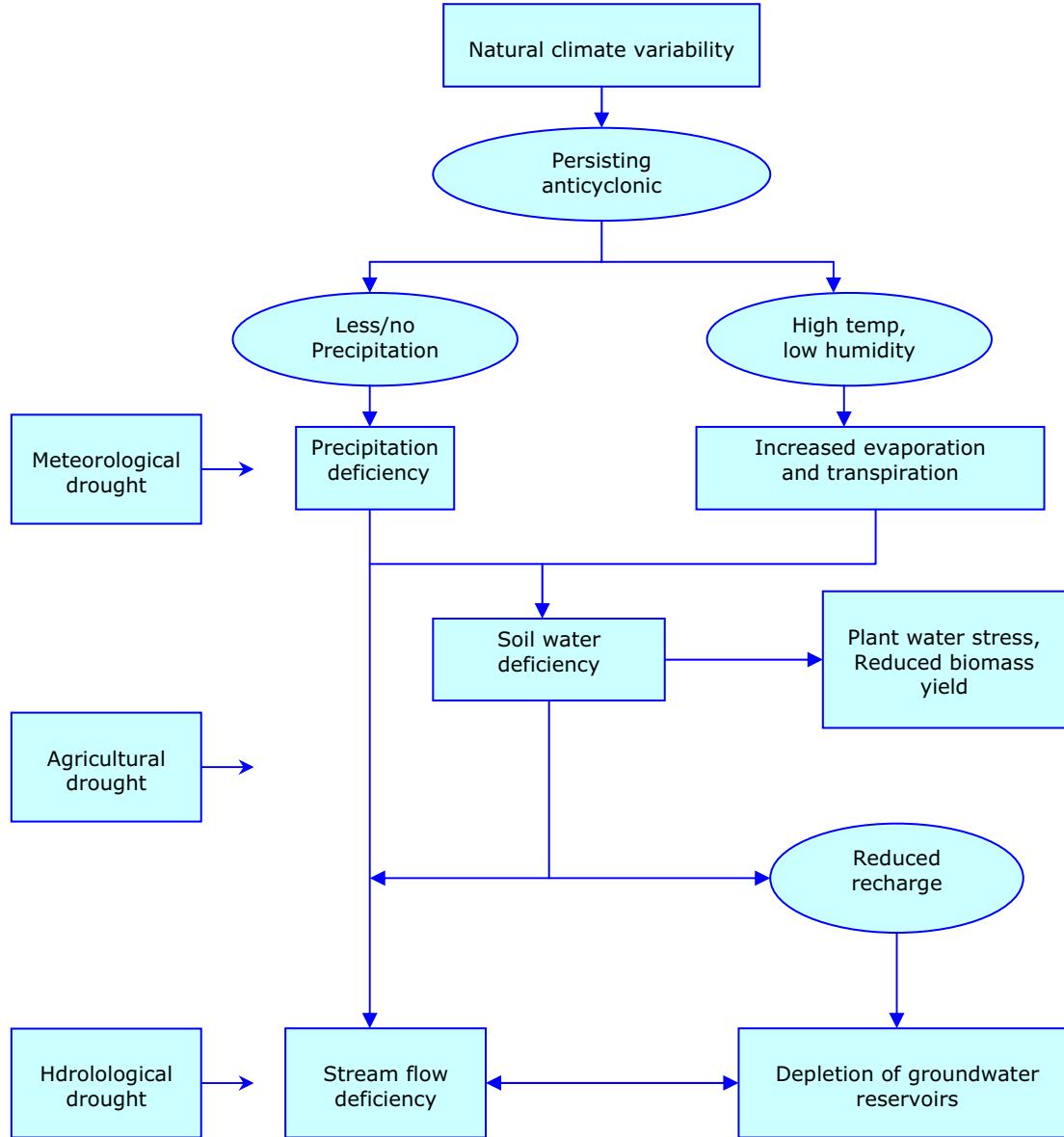
Figure 2 Propagation of drought through the hydrological cycle and its impacts (Source *Tallaksen and Van Lanen 2003*).

1.3 Asian monsoon

Monsoon is a word that comes originally from the Arab ''*Mausin*'' meaning the season of winds. The Asian monsoon is one of several monsoon systems. It refers to the seasonal shifting of winds over the Indian Ocean and surrounding regions, where north-easterly winds prevail during the Boreal winter and south-westerly winds during

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the Boreal summer [*Rao 1976*]. The theory for monsoon was first suggested in the pioneering work of Halley in the 17th century, and since then the paradigm of monsoon has been a giant land-sea breeze driven by land-ocean thermal contrasts. This theory is used, even today, in explanations for the Asian monsoon, e.g., *Anderson et al. [2002], Gupta et al. [2003]*. Moreover, the Asian monsoon or the seasonal changes of winds and rainfall in the region could be interpreted as a result of northward seasonal migration of the east-west oriented precipitation belt called the inter-tropical convergence zone (ITCZ) from the southern hemisphere in winter to the northern hemisphere in summer [*Gadgil 2003*].
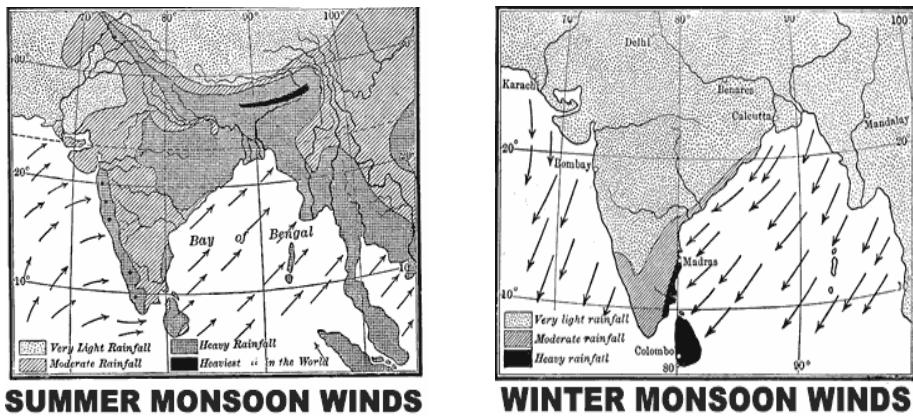
Figure 3 Climatological components of the Asian monsoon (*from Dowling 2005*)

Figure 3 shows the climatological components of the Asian monsoon, both the south Asian summer monsoon (SASM) and the northeast Asian winter monsoon (NAWM). During the Boreal summer, south-westerly winds are prevailing, constituting the so-called south Asian summer monsoon. The winds blow from the ocean to the land and bring rainfall over the region. This is due to the difference in heating between the Asian hot land mass and the cooler ocean causing air masses over the land to heat up, expand, and rise. As the air rises, cooler moister and heavier air from over the ocean will replace it.

During the dry season or the Boreal winter, the winds blow offshore, from land to sea, here called the northeast Asian winter monsoon. The winds from the northeast during the winter months are dry because they have lost their moisture on the Asian land mass. The cold air from the middle of the continent cannot reach a portion of Southeast Asia because the Himalayas act as a wall blocking the cold air mass causing high temperatures and dry weather.

1.4 El Niño, La Niña and Southern Oscillation

El Niño means "the boy" in Spanish and refers to the infant Jesus Christ. This expression was originally used by fishermen along the coasts of Peru and Ecuador to describe the warm southward ocean current that typically appears in their fishing area during the Christmas season and lasts for a few months. The appearance of this

phenomenon would not only decrease the fish production but also bring heavy rain to the arid coast of Peru and Ecuador [*Trenberth 1991*]. The cold-water zones offshore Peru and Ecuador normally support large populations of fish. However, during El Niño a layer of warmer, nutrient-depleted water from the west covers the plankton-rich eastern coastal waters, thereby seriously affecting the fish production, and subsequently, the economy of the region. Over many years, El Niño was considered to be a local phenomenon. That the unusually warm surface water offshore Peru and Ecuador expanded thousands of kilometres towards the central Pacific was realized by oceanographers in the 1960s [*Philander 1990*]. In the early 1980s it became clear that El Niño was closely associated with the Southern Oscillation (SO), an atmospheric phenomenon discovered by Sir Gilbert Walker early in the 1930s [*Battisti and Sarachik 1995*]. The SO is a see-saw in atmospheric mass associated with air exchanges between the eastern and western hemisphere with centres of action located in over Indonesia and the tropical southern Pacific [*Trenberth 1991*]. The two centres of action are presented in Fig. 4. The SO is the atmospheric counterpart of El Niño, and El Niño is the oceanic counterpart of SO. Since El Niño and the Southern Oscillation are related, the two terms are often combined into a single phrase, the El Niño-Southern Oscillation, or *ENSO* for short [*Philander 1990*]. Therefore, ENSO is a result of close interaction between atmospheric and oceanic dynamics in the Pacific Ocean.
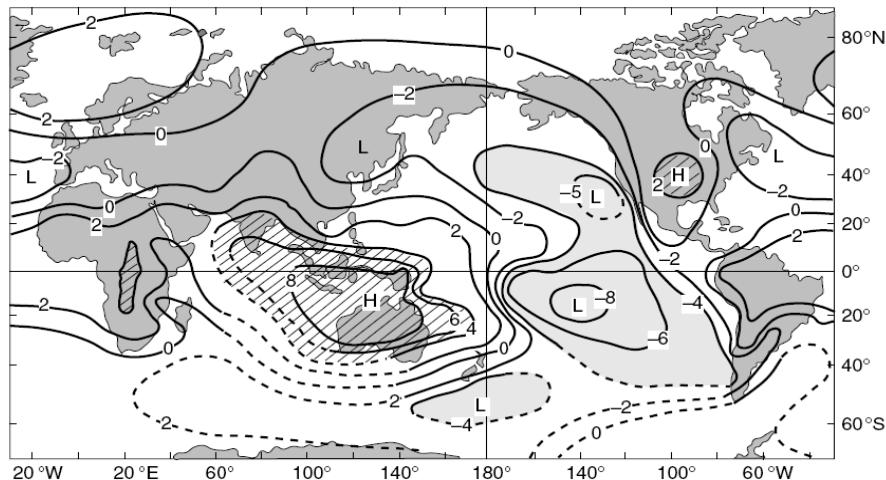
Figure 4 Spatial pattern of annual mean sea level pressure anomalies associated with the Southern Oscillation. Solid cross hatching indicates regions where sea level pressure varies in phase with Darwin, and light shading indicates regions where sea level pressure varies out phase of Darwin. Numbers are correlation coefficients (x10); high values show a more consistent relationship with Darwin (adapted from *Trenberth and Shea 1987*)

As explained in *Trenberth and Shea [1987]* and *Trenberth [1991]*, the Southern Oscillation Index (SOI) was calculated based on the difference in anomalous sea level pressure (SLP) between Tahiti (southeast Pacific) and Darwin (southwest Pacific) to express the intensity and the phase of SO as presented in Fig. 5. The negative values are normally corresponding to El Niño episodes that mean the SLP is higher than normal in

Darwin and lower than normal in Tahiti. Sustained negative SOI values often indicate El Niño episodes. These negative values are usually accompanied by sustained warming of the central and eastern tropical Pacific Ocean. The trade winds relax in the central and eastern Pacific, and the SLP is lower than normal in the eastern Pacific causing a reduction of rainfall over the west, and increased rainfall in the eastern Pacific. This is known as the warm phase of ENSO or El Niño. The opposite, positive values of the SOI are associated with stronger Pacific trade winds, and warmer sea surface temperatures and lower SLP in the western Pacific. Waters in the central and eastern tropical Pacific Ocean become cooler during this time. This is popularly known as a La Niña episode or cold phase of ENSO.
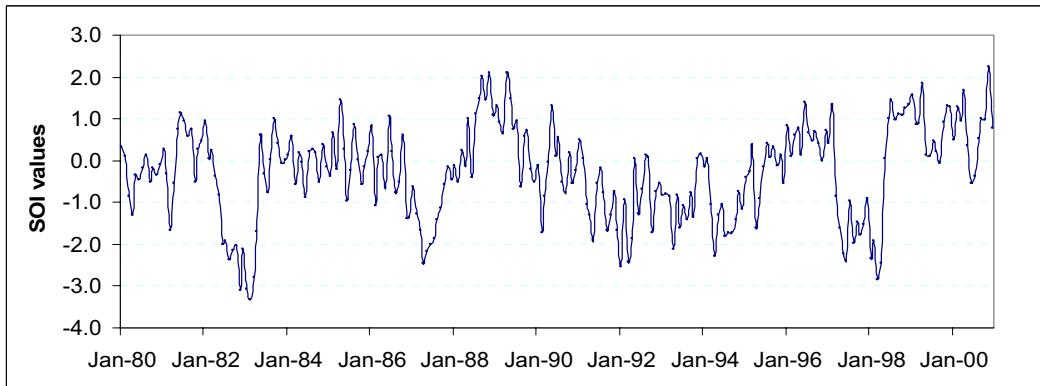
Figure 5 Time series of the monthly smoothed Southern Oscillation Index (SOI) from 1980 to 2000

Figure 6 presents a schematic view of what is defined statistically as, respectively, normal, El Niño and La Niña conditions over the tropical Pacific. As shown in *Trenberth [1991], Wallace [1994],* under normal conditions, the trade winds blow westward across the tropical Pacific resulting in warmer water and a sea water level that is about 50 cm higher in the western tropical Pacific than off-coast of South America. The deep thermocline in the west makes the sea surface temperature more than 10° C higher than the water in the eastern Pacific. The air pressure is quite low over the warmer water. Rising air and deep convection take place over the warmest water causing clouds and heavy rainfall over Indonesia and northern Australia. The rising air displaces eastward and sinks over coldest water, establishing the so-called Walker circulation cell. The sinking air inhibits convection creating the typically arid conditions along the coast of Peru and Ecuador.

During El Niño, the ocean currents are sufficiently warm and persistent to cause a reversal in the normal weather conditions of the eastern and western Pacific. The easterly trade winds relax in the central and western Pacific causing the thermocline to deepen in the east and to shallow in the west. The warm water of the western Pacific flows eastward and sea surface temperatures increase significantly off the western coast of South America. Deep convection moves eastward implying that the warm water and the Walker circulation cell are displaced to the east. This displacement causes strong

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changes in the global atmospheric circulation. Subsequently, the wet weather conditions normally present in the western Pacific move to the east. This brings heavy rains and flooding to South America and can cause the collapse of the monsoons, as well as droughts over Indonesia, northern Australia and regions around *[Halpert and Ropelewski 1992]*.
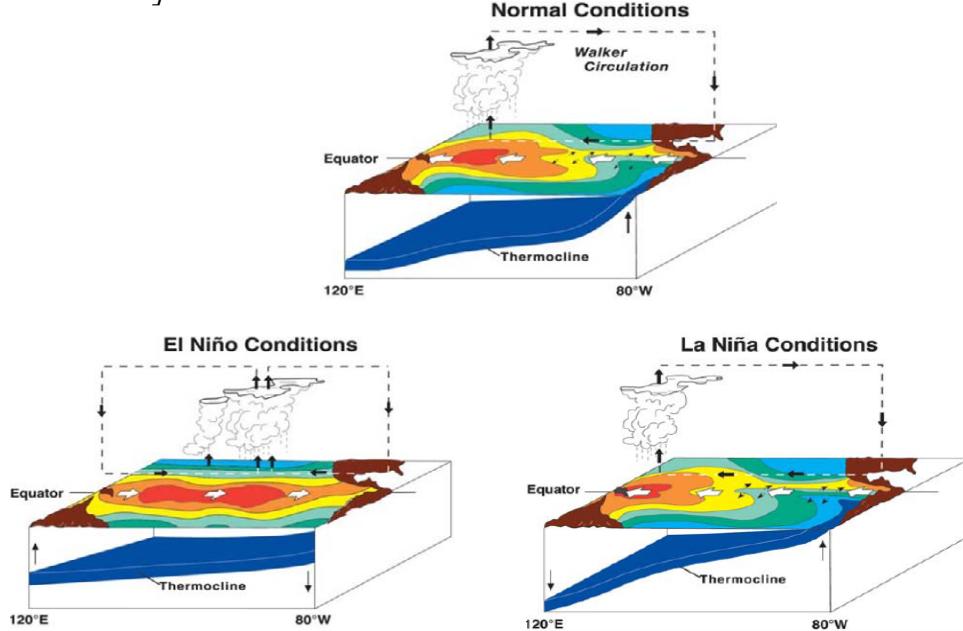
Figure 6 Schematic views of normal, El Niño and La Niña conditions over the Pacific Ocean (adapted from *Wallace 1994*)

The conditions observed in La Niña episodes are opposite of those observed during El Niño. The easterly winds are strengthened causing warmer surface water, lower SLP and deeper thermocline in the western Pacific. On the other hand, the sea surface temperature is colder, the SLP is higher and the thermocline is shallower in the east of Pacific. Convection over the warm water in the west becomes stronger and the raised air sinks over the cold water in the eastern Pacific resulting in a more intense Walker cell over the tropical Pacific. This phenomenon brings heavy rain over the west and drier conditions over the east of the Pacific.

Table 1 shows a summary of the major changes of the oceanic and atmospheric characteristics over the tropical Pacific during ENSO episodes in comparison to normal conditions.

Table 1 Main changes in the ocean and the atmosphere over the tropical Pacific associated to ENSO episodes (source *Uvo 1998*)

Patterns	El Niño episode/low phase			La Niña episode/ high phase		
	W. Pacific	C. Pacific	E. Pacific	W. Pacific	C. Pacific	E. Pacific
SST	colder	warmer	warmer	warmer	colder	colder
Thermocline	shallower		deeper	deeper		shallower
SLP	higher		lower	lower		higher
Winds	eastward	weaker	weaker	westward	stronger	stronger
Convection	weaker	strong	strong	stronger	none	none

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1.5 Effects of ENSO

At the beginning of last century Sir Gilbert Walker noted that the failure of the monsoon was somewhat associated with the Southern Oscillation. The fishermen in Peru and Ecuador knew that the warm current called El Niño would bring rainfall over the region. They did not know that these topics were related and form the global phenomenon now called ENSO.

A series of papers, e.g., *Ropelewski and Halpert [1986, 1987, 1989],* reveal a picture of how the temperature and precipitation are globally affected by the ENSO. *Halpert and Ropelewski [1992]* show that during El Niño, the easterly trade winds collapse or even reverse and the normal convection regions from Indonesia to the central Pacific move eastward causing the displacement of the Walker cell. The shift of the convection region is responsible for the variations in atmospheric circulation and climate around the world. The consequences of the displacement are abnormally dry conditions over the western Pacific (Fig. 7), the Asian monsoon tends to be weaker than normal, subsequently less rainfall is falling, and droughts occur over Indonesia and regions around, while wetter conditions appear along the coast of Peru and Ecuador with abundant rainfall over this region during the warm phase of ENSO. During the cold phases of ENSO or La Niña episodes, a more intense Walker cell occur over the tropical Pacific, the convection over warm water in the western Pacific is stronger than normal, and the monsoon tends to be stronger than normal causing abundant rainfall over the west of the Pacific and the monsoon regions.
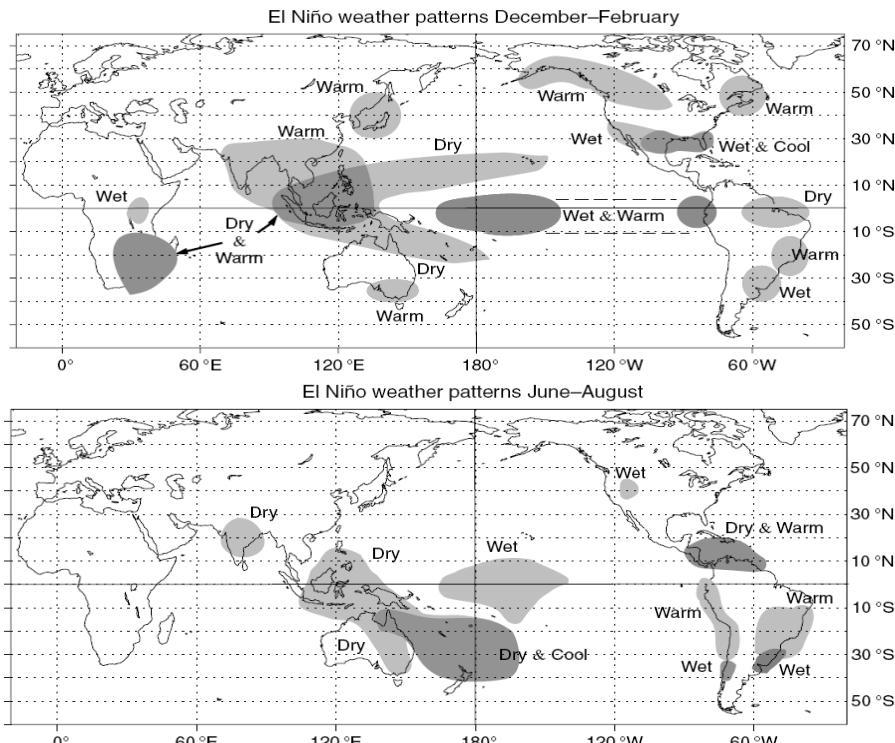

Figure 7 Schematic diagram showing temperature and precipitation anomalies associated with warm ENSO episode during: December to February (upper panel), June to August (lower panel). The impacts of cold ENSO are similar to what can be seen above but with opposite sign (adapted from *Halpert and Ropelewski 1992*)

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ENSO and the SASM are not independent phenomena but part of a coupled ocean-atmosphere oscillation. The interaction between the ENSO and the SASM is complex [*Torrence and Webster 1999*] and has been known since the pioneering work of Sir Gilbert Walker [*Walker 1924*]. The influence of the ENSO on the SASM was explained as being caused by a change in the Walker circulation that impacts on the regional Hadley circulation associated with the SASM, e.g., *Shukla [1987], Goswami [1998]*. In contrast, some studies show that the SASM has influence on the ENSO through the atmospheric circulation over the central and eastern Pacific, e.g., *Kirtman and Shulka [2000]*. However, the relationship between the ENSO and the monsoon has been noticeably weakened since the late 1970s [*Kinter et al. 2002*].

2. The Vietnamese central highlands

2.1 Description of the region

The Vietnamese central highlands (VCH) is located in the southeast of the Indochina Peninsula, between approximately 12° and 15° N and 107° and 109° E. It includes about five million ha of land with two ranges of high mountains in the north and south with elevation ranges from 1000 to 1700 m a.m.s.l, flat basaltic plateaus, and widespread forests with average elevation ranging in the interval 200 to 700 m a.m.s.l. The basaltic area is approximately 1.7 million ha comprising 90% of the total basaltic area in Vietnam and over three million ha of forest accounting for 22% of total forested land. The cultivated area is about 800,000 ha with major crops in the region being paddy rice, coffee, sugarcane and other industrial plants. The population is about four million people, and 80% of the population live in rural and mountainous areas, most of them being minorities. The main part of the water supplies for agricultural activities, households, and livestock depends on about 400 reservoirs and rivers systems in the region.

The catchments of Sesan and Srepok rivers spread from mountainous areas with average elevation ranging from 500 to 1000 m a.m.s.l westward toward the Mekong River System in Cambodia. The Sesan catchment is of about 11,400 km^2, with annual rainfall varying from 1500 to 2300 mm and evapotranspiration about 1000-1400 mm per year. The most upstream areas are comprised by rocky and hard soils that lead to direct rainfall contribution to discharge.

The catchment of Srepok spreads over an area of 12,500 km^2, with steep westward slopes comprised of rocky and hard soil upstream leading to direct rainfall contribution to discharge. The annual evapotranspiration ranges between 1000 and 1400 mm, and the rainfall is approximately 1600 to 2400 mm per year.

The catchment of Ba River spreads over 13,900 km^2 along the eastern parts of the VCH. The river rises from the northern mountain range, flows eastward over the flat plateau with average elevation from 300 to 500 m a.m.s.l, and through the coastal area to the South China Sea. The annual rainfall is about 1700 to 2000 mm and the

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evapotranspiration ranges from 1000 to 1500 mm per year, with maximum evapotranspiration in March and April (120 to 200 mm per month).
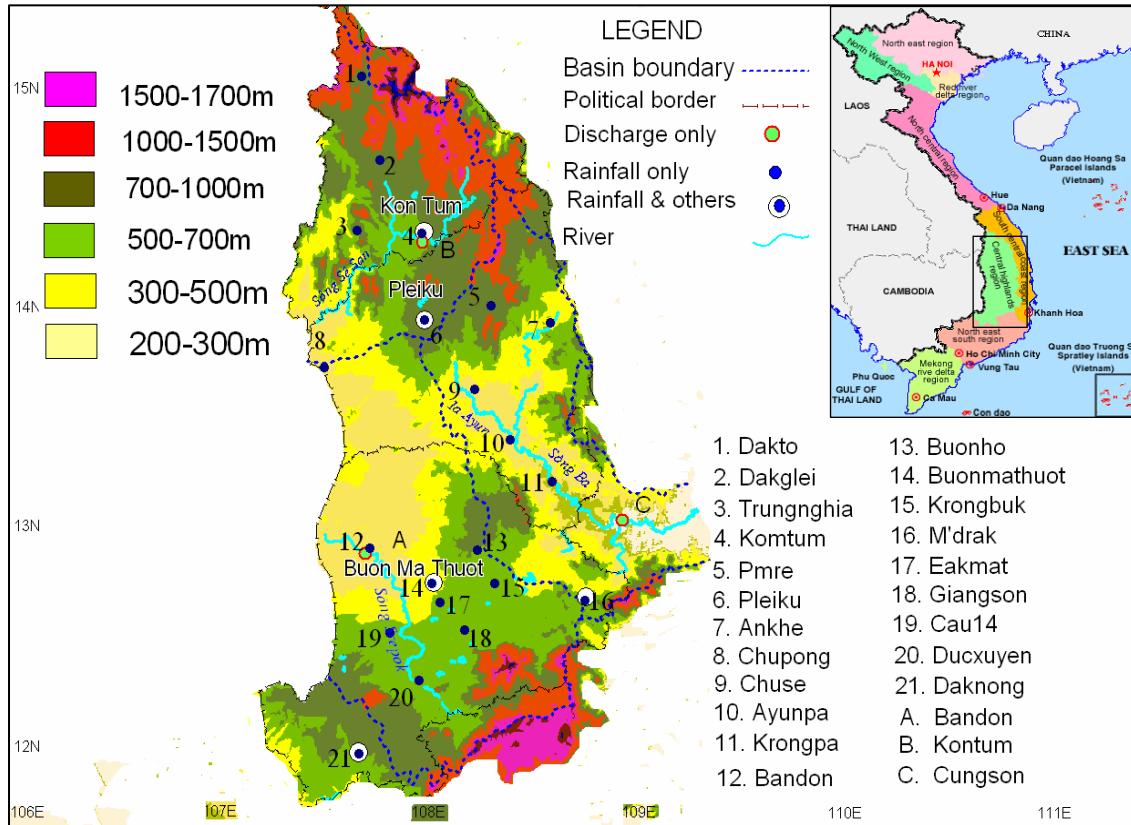
Figure 8 Map of catchments/provinces and distribution of hydro-meteorological stations over the central highlands -Vietnam

2.2 Climate and its variability

The VCH region belongs to the Indochina Peninsula and is embedded in the Asian monsoon system. The south Asian summer monsoon and the northeast Asian winter monsoon are related to a wet and a dry season, respectively [*Zhang et al. 2002*]. The wet season occurs from early May to mid-October, whereas the dry season is from November to April. The early rainfall over the VCH is associated with the appearance of strong convection indicating the start of the SASM [*Lau and Yang 1997*].

The interannual variation of rainfall is mainly caused by the westward-propagating weather disturbances expressed by short wave train anomalies emanating from the western tropical Pacific [*Chen and Yoon 2000; Chen and Weng 1999*] and an east-west interannual see-saw responding to the Walker circulation for the Indo-Pacific interannual interaction [*Chen and Yoon 2000*]. Moreover, the rainfall in the Boreal summer is a result of northward seasonal migration of the rain belt referred to as the intertropical convergence zone (ITCZ) [*Gadgil 2003*].

The interannual variations of the rainfall are mainly influenced by seasonal winds. Fig. 9 shows the normal (1980-2000) monthly rainfall and temperature over the VCH. The annual rainfall ranges from 1500 to 2400 mm. Monthly rainfall concentrates

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from May to October accounting for about 80% of the annual rainfall amount. The average monthly rainfall during the rainy season exceeds 200 mm. The peak of rainfall is observed in August and September due to tropical cyclones and typhoons during this period. The air temperature ranges from 20 to 25°C. The highest temperatures are observed in April and May, corresponding to rapid warming of the landmass that causes the onset of the SASM with atmospheric circulation over mid and low latitudes [*Yanai et al. 1992*].
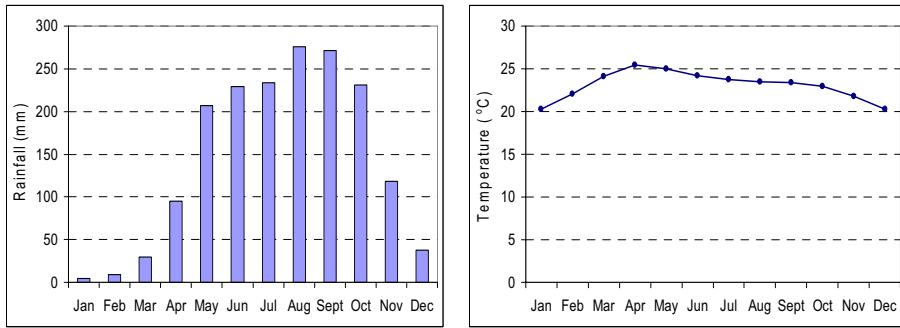
Figure 9 Normal (1980-2000) monthly rainfall and monthly air temperature over the Central highlands, Vietnam

Teleconnections between rainfall over Vietnam and global climate variability in terms of El Niño and the Southern Oscillation have been extensively studied. Most studies focus on the impacts of ENSO on climate in Vietnam, especially during extreme ENSO events, e.g., *Tang [1998], Duy [1998]* and *Ninh [1999].* Their results show that during the El Niño episodes, the SASM is weaker than normal, and the atmospheric turbulence causing rainfall during the monsoon tends to decrease due to the warm anomalies of SST in the central equatorial Pacific that shift the origin of storms to the southeast Pacific. The weather in Vietnam, as part of the global weather system, is influenced by large-scale circulation. El Niño and La Niña that occur normally every two to seven years have strongly affected the weather in many places of the world, including Vietnam [*Tang 1998; Lien 1999*]. *Tang [1998]* shows that El Niño is a global weather change issue, amongst the El Niño events of the 20th century, the 1982/83 and 1997/98 events were strongest and had severe impacts on the environmental and socio-economic sectors of Vietnam. The relationship between El Niño and the weather in Vietnam has been described by, e.g., *Duy [1998], Tang and Thi [1999]. Ngu [2000]* reveals that the ENSO affects more clearly the areas in the south than in the north of Vietnam. However, its consequences depend on the response of natural calamities in individual regions to those events.

Figure 10 shows the variations of SST anomalies during the extreme El Niño event 1997/98 in Niño3 (5°S-5°N; 150°W-90°W). It begins in early March 1997, reaches the peak in the early 1998, lasts until May, and then shifts to a La Niña episode. The variation of monthly rainfall anomalies over the VCH during the extreme El Niño 1997/98 is presented in Fig.11. It can be seen that the relationship between rainfall over

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the VCH and SST in Niño3 is complex during 1997, some months present rainfall deficiency and other months show abundance of rainfall in comparison to the average. During early 1998, El Niño reaches its peak and lasts until May. During this period, the rainfall drops below normal and causes severe, massy a drought over the region until September, according to statistical records obtained from the national Hydro-meteorology Institute.
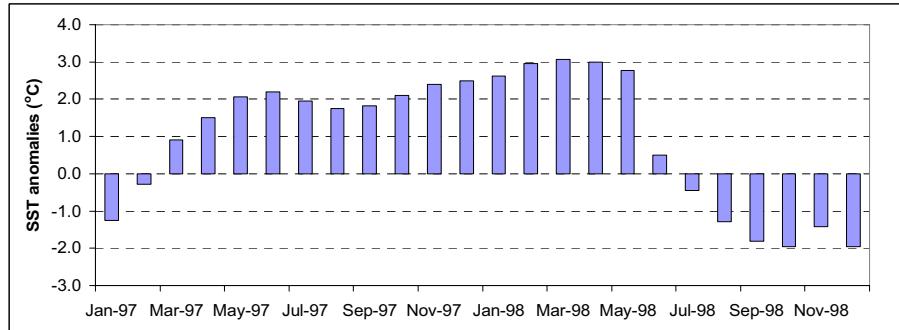
Figure 10 SST anomalies in Niño3 region during the 1997/98 El Niño episode
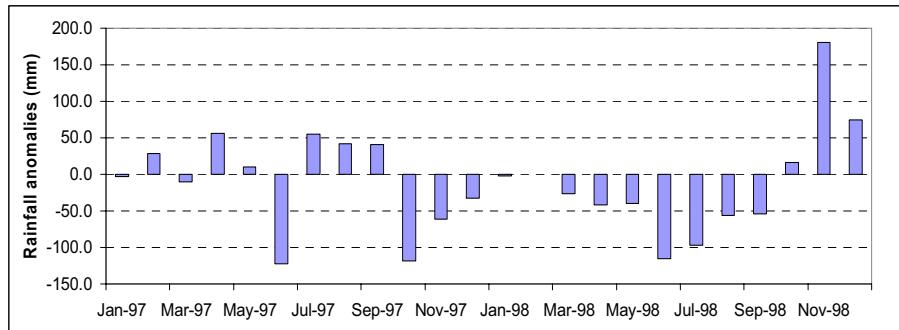
Figure 11 Monthly rainfall anomalies over the Vietnamese central highlands during the 1997/98 El Niño episode

2.3 Drought issues in the central highlands

2.3.1 Natural causes

Drought is considerable as a natural hazard [*Wilhite 2001*], which is a consequence of a water availability deficit during a certain period of time. According to statistical records obtained from the national Hydro-meteorology Institute, droughts have been observed in the VCH since the 1980s due to changes of global weather patterns and regional characteristics such as deforestation. Rainfall over the VCH is abundant but not well temporally distributed through the year, being concentrated for some months in a rainy season that accounts for about 80% of the annual amount and is mainly governed by the Southeast Asian summer monsoon, ITCZ and typhoons, which are influenced by large-scale circulations. These circulations combined with surface characteristics such as topography lead to different precipitation distributions and hydrological mechanisms over the region [*Xuan 1999*]. A break phase or a delayed onset of the SASM and variability in the strength and location of the ITCZ might lead to

drought occurrence over the VCH. The global phenomenon known as El Niño and Southern Oscillation has a significant influence on weather over Vietnam, and the teleconnections between such phenomena and drought occurrences over Vietnam have been concerned and studied by scientists, e.g., *Hien and Ninh [1988],Tang and Thi [1998]* and *Tang [1998]*. They conclude that droughts over Vietnam are strongly related to ENSO. In the other words, drought occurrence over Vietnam is to a large extent caused by El Niño-Southern Oscillation.

2.3.2 Human causes

Drought is mainly caused by the global weather changes discussed above, which depend on many factors, among them human activities, which are considered as new factors that have influenced the changes of the global climate significantly during the last few decades [*Adger 1998*]. Drought is not only caused by natural phenomena but also human activities, and lack of policies in many developing countries can cause drought or make a drought situation more aggravated [*Hoc 2002*].

The quick population growth has led to lack of arable land and insufficiency of products to support an increasing demand in the region, and subsequently parts of the forested land over the VCH have been changed to arable and residential land. The production and land use are only based on short-term objectives and not on a long-term strategy for environmental protection and sustainable development [*NAP 2002*]. This is one of the major reasons for unsustainable land use and nature resources management, which increase the potential vulnerability of the region to drought events.

Long-term planning is lacking behind, e.g. development plans for natural resource utilization over the VCH such as land use, forests, water resources, biodiversity etc. The same applies to legal documents and guidelines for institutions. This implies less local resource mobilization and encouragement related to exploitation and management of natural resources. Moreover, planning, management, and decision-making at the local level in the VCH do not fully meet the requirements for economic development to become sustainable, which enhances the vulnerability of the region to drought phenomena.

2.3.3 Impacts

Statistical records carried out by the national Hydro-meteorology Institute show that the consequent impacts of droughts on the environmental and socio-economic sectors of Vietnam in general, and in particularly of the VCH, are comparable to damages caused by floods and typhoons. A deficit of rainfall over a certain period in combination with high temperature and high potential evaporation may lead to huge deficiencies of the water supply over the region, which subsequently may turn into a large-scale drought with impacts on the water using sectors, e.g., losses in agricultural production, emerging of forest fires, and reservoir depletion, as well as on related sectors causing, e.g., famine, diseases, conflicts etc.

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Prolonged droughts can seriously affect society in large regions. The shortage of water does not only affect agriculture but also other economic sectors and society as well. Ecological and economic impacts are always closely linked together with social impacts [*Lien 1999*]. Due to the limitation of statistical figures on all sectors affected by drought events since the 1980s in Vietnam, only little information was obtained on the severe drought event related to the 1997/98 El Niño episode, which was considered as the strongest event in the 20th century. Most regions in Vietnam, especially regions in the central to the south, were significantly affected by severe drought causing adverse impacts on livelihood and the national economy. According to a drought assessment of the Ministry of Agriculture and Rural Development, in 1997/98 about 3 million people were affected and the total losses in terms of agricultural production were estimated to about 400 million US dollars. In addition, diseases related to the lack of food, water sanitation and hot weather were observed. Some diseases became epidemics during the drought event, about 250,000 people were infected by dengue fever in Vietnam [*Lien 1998*]. There were no statistics on other sectors such as fishing and ecosystem losses, recreation and tourism etc but all of them were considerably affected [*Lien 1999*].

Due to the lack of impact assessment on the environmental, economic and social sectors in the VCH, only some studies aim at assessing the impacts on agriculture over the VCH. *Hoc [2002]* reveals a series of drought events in the VCH from 1994 to 1998 that affected winter-spring crops. Especially a widespread drought event occurred in 1997/98, which led to huge consequences for the agricultural production in the VCH; about 24,000 ha of winter-spring crops were affected in which over 7800 ha were fully destroyed. For summer crops, over 13,000 ha were affected in which more than 2000 ha were fully destroyed. In total over 110,000 ha of other perennial, industrial plants were affected by the drought, and about 20,000 ha of these were fully destroyed. *Lien [1999]* shows that the widespread drought in 1997/98 was clearly related to the El Niño event, the rainfall of the rainy season in 1998 was about 10 to 50% lower than normal rainfall, and it caused a widespread water shortage in the region and the whole country as well. During the early six months in 1998, there were 60 forest fires over the VCH, which destroyed over 1500 ha of forests. The prolonged drought event in 1997/1998 led to water shortage and depletion in almost all reservoirs, and about 800,000 residents suffered from lack of fresh water over the VCH [*Lien 1999*].

2.4 Data description

The data used comprise hydrological data such as monthly discharge, and meteorological data sets such as monthly precipitation, air temperature, humidity, and wind speed. These data were taken from the national Hydro-meteorology Institute for the period 1980-2000. A network of 21 selected, well-distributed meteorology gauging stations and three hydrology gauging sites in three rivers catchments over the VCH was used in the thesis, as presented in Fig. 8. Precipitation data sets were used to investigate the influence of SST on monthly precipitation over the VCH (in **paper I**), and rainfall

and discharge data sets were used in order to develop linear (in **paper II**) and non-linear forecast models (in **paper III** and the **technical report**).

Meteorological data sets: The rainfall records were collected at all stations available over the VCH. The data had previously been quality controlled by the national Hydro-meteorology Institute. Only station records with no more than 10% missing data in the interval from January 1980 to December 2000 were selected, summing up to 21 stations over the VCH (Fig. 8). Of the selected records the maximum amount of missing data was 9.5% and the average was 2.8%.

For a station presenting more than 3% of monthly missing data, or a whole year of missing data, a multiple linear temporal regression was established based on rainfall records from nearby, highly correlated stations. After this step, only two stations with missing data remained in the records. These remaining gaps were filled-in by inserting appropriate long-term means. Moreover, other meteorological variables such as air temperature, humidity, and wind speed at five available stations were used.

Hydrological data sets: Monthly discharge at three stations were used in three catchments, namely the Sesan, Srepok and Ba river basins (Fig. 8), spanning the period from January 1980 to December 2000. Like the meteorological data sets, these data were previously quality controlled by the national Hydro-meteorology Institute, and there were no missing data at the selected stations.

SST data from the tropical range of the Pacific and Indian oceans, i.e. (28°N-28°S; 120°E-85°W) and (28°N-28°S; 30°E-105°E), were obtained from the Comprehensive Ocean Atmosphere Data Set (COADS) [*Reynolds et al. 2002*], and extracted from the data library of the International Research Institute for Climate and Society-IRI. The data, available at a 2°x2^{o} lat-long grid point resolution, were transformed to a 4° x 4° lat-long resolution by simple averaging for the purpose of the current study. These data sets were used in **paper I**, **II**, and **III** and the **technical report**.

3. Selected methods and application

In **paper I,** singular value decomposition was selected to investigate the influence of SST in the Pacific and Indian oceans on precipitation over the VCH. Subsequently, in **paper II**, canonical correlation analysis was used to develop linear models for rainfall forecasts at selected stations over the VCH, and in **paper III** non-linear techniques known as artificial neural networks were utilized to develop non-linear models for rainfall and discharge forecasts. Due to relative short available time series, cross-validation was used in **paper II** and **paper III** to show the generality of the selected models.

3.1 Singular value decomposition

Singular value decomposition was comprehensively described by *Bretherton et al. [1992]* and amongst others related to the current topic by *Wallace et al. [1992, 1993], Uvo [1998]* and *Uvo et al. [1998]*. What follows in this section is based on these references.

3.1.1 Theory

Let two fields of data be $Y_{t,y}$ and $Z_{t,z}$ varying both in space (*y* and *z*) and in time (*t*).The time t has *nt* steps that must be the same for Y and Z. The spatial dimensions y and z have *ny* and *nz* space points, respectively. Both Y and Z have zero mean per column. Let the directions of optimal covariance for Y and Z be given by the vectors G and H, respectively. When Y and Z are projected onto G and H, respectively, we obtain two new vectors U and V, defined as follow:

$$U= YG \qquad\qquad (1)$$

$$V= ZH \qquad\qquad (2)$$

The cross-covariance matrix between Y and Z can be written: $C_{YZ} = \dfrac{1}{nt-1} Y'Z$

where Y' is Y transpose.

The covariance between U and V is defined:

$$Cov(U,V) = \frac{1}{nt-1} \sum_{t=1,nt} U_t'V_t \rightarrow \max \qquad\qquad (3)$$

What we need to do now is to find a pair of vectors G and H that are linear combinations of Y and Z and explain most of the total covariance between Y and Z. In other words, we need to find the vectors G and H that maximize equation (3) above.

From (1), (2) and (3) follows:

$$Cov(U,V) = \frac{1}{nt-1} G'Y'ZH \Rightarrow G'C_{YZ}H \rightarrow \max$$

When solving maximization problems, the constraints must be considered. Since the total variance of each field equals one, we have:

$$G'G = H'H = 1$$

To maximize the covariance function under the given constraints, the following Lagrange expression is introduced:

$$F(\alpha,\beta,G,H) = G'C_{YZ}H - \alpha(G'G-1) - \beta(H'H-1) \qquad\qquad (4)$$

Taking derivatives with respect to G' and H gives

$$\frac{\partial F}{\partial G'} = C_{YZ}H - \alpha G = 0 \qquad\qquad (5)$$

$$\frac{\partial F}{\partial H} = G'C_{YZ} - \beta H' = 0 \qquad\qquad (6)$$

Rescaling (5) and (6) by pre-multiplying with G' and post-multiplying with H, respectively, yields:

$$G'C_{YZ}H = \alpha = \beta = \max \mathrm{covariance}$$

Transposing (6) with respect to H, knowing that $C'_{YZ} = C_{ZY}$, and applying and rearranging (5) give the following equation for the vector G:

$$(C_{YZ}C_{ZY} - \alpha^2 I)G = 0$$

where α^2 are eigenvalues of $C_{YZ}C_{ZY}$, G is the eigenvector, and I denotes the identity matrix.

3.1.2 Method

The Singular Value Decomposition (SVD) will produce components of any matrix A_{nm}, $SVD(A_{nm}) = G_k \alpha H'_k$, where G_k and H_k are orthogonal and α is an $n_x m$ diagonal matrix with non-negative diagonal values, called the singular values or eigenvalues, $\alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \ldots \geq \alpha_{\min(n,m)} \geq 0$. G_k is the left-field singular vector or eigenvector, H_k is the right one, and k is the number of modes of eigenvectors.

Once SVD is applied to the cross-covariance matrix (C_{YZ}) between two fields, say $Y_{nt,ny}$ (left field) and $Z_{nt,nz}$ (right one), it identifies the pairs of spatial patterns that explain most of the temporal covariance between the two fields. When two eigenvectors, G_k and H_k, are obtained from SVD, homogeneous and heterogeneous correlation maps can be easily produced [*Bretherton et al. 1992*]. The kth homogeneous map is defined as the vector of correlations between grid point values of one field with the kth mode of the singular vector of the same field; this map indicates geographic covariance of variables in one field. The kth heterogeneous map is identified by the vector of correlations between grid point values of one field with the kth mode of the eigenvector of the other field; this map implies how well the grid points of one field relate to the kth mode of the singular vector of the other field.

The total squared covariance displayed by two eigenvectors (G_k,H_k) is α_k^2. The maximum covariance is corresponding to the highest singular value that is obtained by projecting the left field onto the first singular vector of the right field and projecting the right field onto the first eigenvector of the left field. The normalized squared covariance (NSC) is defined by *Wallace et al. [1993]* to present the extent of relationship between the left field and the right field in modes obtained from SVD. NSC ranges from zero, when the two fields are completely unrelated, to one, when the two fields are perfectly related to each other.

$$NSC_k = \left[\frac{\alpha_k^2}{\sum_i \sum_j \text{var}_i \, \text{var}_j} \right]^{\frac{1}{2}}$$

where var$_i$ and var$_j$ are the variance at the ith grid point in the left field and the jth grid point in the right field, respectively.

3.1.3 Applications

SVD is a generalization of the diagonalization procedure for matrices that are not square or symmetrical. The technique is applied to the cross-covariance matrix between two data field sets [*Bretherton et al. 1992*]. The use of SVD allows isolating sets of orthogonal pairs of spatial patterns with maximum squared temporal covariance between two physical variables. The first use of SVD in a climatologic context was made by *Prohaska [1976]. Wallace et al. [1992]* show the application of SVD for a geographic problem and demonstrate that SVD is the best one among the techniques compared. SVD has also been applied in other studies associated with climatology, e.g., *Lanzante [1984], Hsu [1994],* and *Lau and Nath [1994]*.

SVD is a powerful tool for objectively detecting coupled patterns between two fields. In **paper I**, SVD is used to determine the relationship between SST in the tropical Pacific and Indian oceans and precipitation over the VCH. The patterns shown by the heterogeneous correlation map indicate how well the precipitation (SST) anomalies pattern relates to the kth expansion coefficient of the SST (precipitation) anomalies pattern. Moreover, NSC is used to identify the strength of relationship between SST and precipitation fields. The analyses are considering both simultaneous and time-lagged data.

A test of the null hypothesis based on the Student's t-distribution as presented in *Bendat and Piersol [1986]* was used to determine whether the correlation coefficients of the heterogeneous correlation maps differed significantly from what can be expected by chance.

3.2 Canonical correlation analysis

This section is based on of literature dealing with theory and model applications of canonical correlation analysis including *Barnett and Preisendorfer [1987], Bretherton et al. [1992], Uvo [1998], Uvo and Graham [1998]* and, amongst others, also *Gershunov and Cayan [2003],* and *Ntale et al. [2003]*.

3.2.1 Theory

Suppose we have two fields of data, say $Y_{t,y}$ and $Z_{t,z}$, where the subscripts illustrate time (t) and space (y and z). Time t has *nt* steps that must be the same for Y and Z. The spatial dimensions y and z have *ny* and *nz* space point, respectively. Data of

each column has zero mean. When Y and Z are projected onto R and Q, respectively, we obtain two new vectors U and V, defined as follow:

$$U = YR \qquad (1)$$

$$V = ZQ \qquad (2)$$

The correlation between U and V is given as follows:

$$Cor(U,V) = \frac{\sum UV}{\sqrt{\sum U^2 \sum V^2}} \rightarrow \max \qquad (3)$$

Likewise the case of SVD, we here need to find a pair of vectors R and Q that are linear combinations of Y and Z, respectively, and maximize equation (3).

If Y is the data set and R is the transformation, then U is the transformed data set, and the variance of U is defined by:

$$\text{var}(U) = \frac{\sum U^2}{nt-1} = \frac{U'U}{nt-1} = \frac{R'Y'YR}{nt-1} = R'S_{YY}R$$

where $\dfrac{Y'Y}{nt-1}$ is the covariance matrix (S_{YY}) of Y, and

$$\sum U^2 = R'S_{YY}R$$

Following the same procedure for Z and for the cross-covariance between Y and Z gives:

$$\sum V^2 = Q'S_{ZZ}Q \quad \text{and} \quad \sum UV = R'S_{YZ}Q$$

where $S_{YY} = \dfrac{Y'Y}{nt-1}$; $S_{ZZ} = \dfrac{Z'Z}{nt-1}$; and $S_{YZ} = \dfrac{Y'Z}{nt-1}$

Now (3) becomes:

$$Cor(U,V) = \frac{R'S_{YZ}Q}{\left(R'S_{YY}R x Q'S_{ZZ}Q\right)^{\frac{1}{2}}} \rightarrow \max \qquad (4)$$

Note that rescaling data does not affect the correlation and that the total variance in each field is equal to one, implying that the constraints should be identified:

$$R'S_{YY}R = 1, \text{ and } Q'S_{ZZ}Q = 1$$

As $F(R,Q) = R'S_{YZ}Q$ is the function that needs to be maximised, Lagrange multipliers are introduced as follows:

$$F(\alpha,\beta,R,Q) = R'S_{YZ}Q - \alpha(Q'S_{ZZ}Q - 1) - \beta(R'S_{YY}R - 1) \qquad (5)$$

Solving equation (5) by taking derivatives with respect to R' and Q yields:

$$\frac{\partial F}{\partial R'} = S_{YZ}Q - \beta S_{YY}R = 0 \qquad (6)$$

$$\frac{\partial F}{\partial Q} = R^{'}S_{YZ} - \alpha Q^{'}S_{ZZ} = 0 \tag{7}$$

Rescaling (6) and (7) by pre-multiplying with R' and post-multiplying with Q, respectively, and making use of the constraints produce:

$$R^{'}S_{YZ}Q = \alpha = \beta = \max \text{correlation}$$

Transposing (7) with respect to Q, and applying and rearranging (6) give the equation for the vector R:

$$(S_{YY}^{-1}S_{YZ}S_{ZZ}^{-1}S_{ZY} - \alpha^2 I)R = 0$$

where α^2 are the eigenvalues of $S_{YY}^{-1}S_{YZ}S_{ZZ}^{-1}S_{ZY}$ and I is an identity matrix.

The vector α^2 contains the squared correlation coefficients relating U to V, and the eigenvectors $R_{ny,nm}$ contain the weights for transforming Y to U. The eigenvectors $Q_{nz,nm}$ contain the weights for transforming Z to V. Thus, these eigenvectors can be used to construct the canonical spatial patterns U and V, or linear combinations of the canonical component vectors:

$$U_{nt,nm} = Y_{nt,ny} R_{ny,nm}$$

$$V_{nt,nm} = Z_{nt,nz} Q_{nz,nm}$$

where

nm: number of canonical modes

nt : number observed points of data

ny, nz : number grid points in the data field Y and Z, respectively

3.2.2 Linear model

Conceptually, canonical correlation analysis (CCA) is a product of least squares multiple regressions. It can be used to develop models for prediction of a particular point in a predictand field based on the evolution patterns of values in another field, called the predictor field.

Suppose that Y denotes the predictor field, and Z indicates the predictand field. The model is generated by calculating a matrix of regression coefficients (S), which correlates the canonical component time series of the predictor field (U) to the individual points in the predictand field (Z). Because U is orthogonal and the total variance equals one, the matrix of correlation coefficients $S_{m,z} = (U_m Z_z)$ relates the canonical modes or component time series of the predictor field to z grid points in the predictand field. Here m indicates the canonical mode of the predictor field, and z shows the number of grid points in the predictand field (Z). Therefore, the multiple regression equation can be presented in matrix form as $Z^{est} = U^{'}S$, where Z^{est} is a matrix of estimated values of Z. This constitutes the so-called CCA model.

In CCA model development, not all modes of canonical components are used. Only statistically or physically significant modes are kept in order to avoid the model being developed on the basis of noise fitting. In such way, the major features of the temporal and spatial variations of the predictor and predictand fields will drive the model.

3.2.3 Applications

The CCA is a linear multivariate technique. Its early version was introduced by *Hotelling [1935, 1936],* and it has been used widely in the social sciences since the 1960s [*Bretherton et al. 1992*]. The CCA has been commonly used for both diagnostics [*Nicholls 1987; Díaz et al. 1998*] and prediction studies [*Glahn 1968; Barnett 1981; Barnett and Preisendorfer 1987; Barnston and Ropelewski 1992; Gershunov and Cayan 2003; Ntale et al. 2003*]. CCA is able to define the highest spatial and temporal evolution of the predictor field that best predicts the predictand field. Within this context, in **paper II**, CCA is used to forecast monthly rainfall over the VCH throughout the rainy season based on monthly SST in the tropical Pacific and Indian oceans. The correlation coefficients between estimated and observed values are used to assess the quality of the forecasts.

3.3 Artificial neural network

3.3.1 Introduction

How the human brain trains itself to process information is still not fully understood. *Cuong and Phuoc [2001]* introduce how the human brain generally works, as presented in Fig. 12. A neuron receives signals from other neurons through a network of nerve fibres called *dendrites* into the cell body. The cell body sums and thresholds the incoming signals. The neuron sends out the signal to others through a single fibre called *axon*, which splits into thousands of branches. The connection between the axon of a cell and the dendrites of another is called a *synapse*. The synapse converts the signals from the axon into electrical effects, which inhibit or excite the activity in the connected neurons. *Hagan et al. [1996]* show that the function of the natural neural network is established by changing the effectiveness of the synapses so that the influence of one neuron on another changes. Some of neural structures are defined at birth, while others are developed through learning life. Thus, learning in biological systems is to adjust the synaptic connections that exist between the neurons.

An Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way the biological nervous system in a human brain function. Conceptually, the ANN is composed of simple elements working in parallel. Mathematically, ANN is a theorized mind model in which the network function is determined by interconnecting elements in the system. Therefore, a neural network can perform a non-linear complex relationship through a training process by adjusting the weights that link interconnected elements in the network.
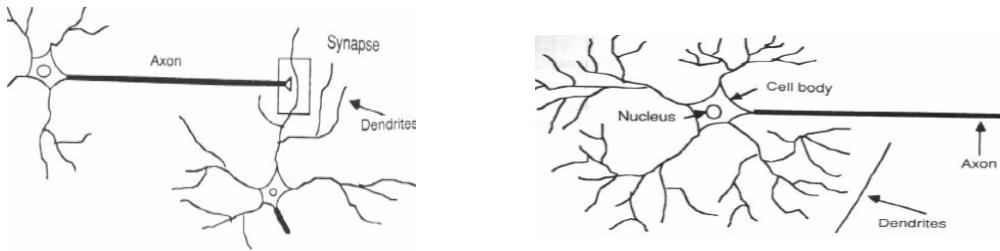
Figure 12 Components of a human neuron (right) and its synapse (left) (adapted from *Cuong and Phuoc 2001*)

3.3.2 The concept

Artificial Neural Networks are comprehensively described by *Bishop [1995]* and reviewed by, e.g., *French et al. [1992], Hsu [1995], Uvo [1998], Uvo et al. [2000],* and *Dason and Wilby [2001]*. What follows is a brief compilation based on these references.

The basic principle concept of ANN is similar to simple polynomial curve fitting, which is used to solve problems of a dataset with N points by the technique of minimizing an error function.

$$F(x) = w_0 + w_1 x + w_2 x^2 + ... + w_k x^k = \sum_{i=0}^{k} w_i x^i \qquad (1)$$

The function (1) shows the non-linear relation between F and x, where F is the output and x, the input. The precise form of the function can be displayed by the parameters w_i that correspond to the weights in a neural network. The polynomial can be presented briefly as F=F(x,w).

Suppose we have a data set with N points (n= 1, 2, 3,…, N), and each point contains a pair of values referred to as (x_n, y_n), where y_n denotes a desired value called the target value. In order to find optimal values for w (weights) in the predicted function $F(x_n, w)$, the standard curve-fitting procedure involves minimizing the sum of squared errors:

$$E = \frac{1}{2} \sum_{n=1}^{N} (F(x_n, w) - y_n)^2 \qquad (2)$$

E is a function of w so equation (1) can be fitted to the data by choosing an optimal weight that minimizes (2). From (1) and (2) we can see that F(x) is linearly related to w, and E is a quadratic term. This implies that a minimized value of E can be found from a set of linear equations.

Network architectures

An ANN is generally considered as a network of interconnected neurons as presented in Fig. 13. It comprises an input layer, one or more hidden layers and one output layer. There are neurons in each layer; each neuron contains a number of input variables (from input or other neurons) and a number of outputs to other neurons. A neuron calculates a weighted sum based on inputs received, and then it simulates an

output by the transfer function based on the weighted sum. The output is then used as the input to the other neurons in the next layer, or compared to a target if it is the output layer.
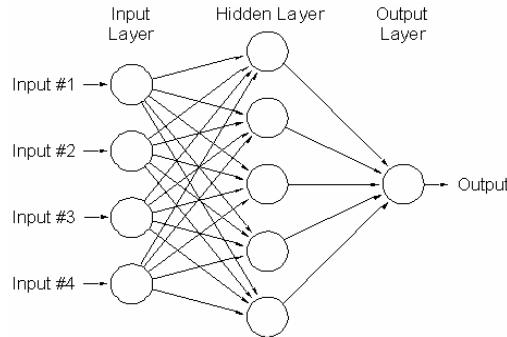
Figure 13 A feed-forward artificial neural network structure

A structure of ANN is based on the objective of a particular problem. Generally, it is a time-consuming process, and the best way to define an appropriate structure of ANN is through tests and trials. Firstly, the number of hidden layers and transfer functions for the neurons needs to be specified. The second task is to identify the number of neurons in each hidden layer. A good option for determining the number of neurons in each layer is to begin with a small number of neurons and gradually increase the network size until an acceptable accuracy of the network is achieved.

Network training

When the network design is identified, the training process needs to be carried out. The training process is taken based on a number of training samples called the calibration dataset, where each one consists of a specific input pattern and a corresponding desired output pattern or a target. The training process is to adjust the weights that link neurons to enhance the network generating the output, until it reaches the target with an acceptable level of accuracy. In this step, some more difficulties are encountered because the transfer functions are normally highly non-convex and high-dimensional so that they contain huge local minima with extensive regions, which are very insensible to variations of the weights [*Hsu et al. 1995*].

Back propagation was created by generalizing learning rule to multiple-layer networks and different nonlinear transfer functions. Input and the corresponding target are used to train a network until it can fairly well approximate a function. The term back propagation refers to the manner in which the gradient is computed for nonlinear multilayer networks. There are a number of variations on the basic algorithm that are based on other standard optimization techniques, such as conjugate gradient and Newton methods. The training is finished when an acceptable minimum error is reached, or a given number of training epochs is completed [*French et al. 1992*].

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Network generalization

When the training process is finished, the output of an ANN can approximate fairly well a function that expresses the relation of the input and the target in the calibration dataset. The main objective of ANN is to generate the target values from given inputs not belonging to the calibration dataset, the so called generalization or validation.

As suggested by *Uvo et al. [2000]*, some necessary conditions should be considered through the training process in order to obtain a good generalization of an ANN model. One important requirement is that the input should contain sufficient information pertaining to the target. Another requirement for a good generalization is that the learned function needs to be smoothened to a certain degree before applying it to ANN models. The third condition is that the dataset used for the training process should be representative for all cases. Moreover, cross-validation method can be used in ANN in the case of relatively short available data set.

3.3.3 Applications

ANNs have been used in climate and hydrological sciences during recent years. *Dawson and Wilby [2001]* present a thorough review of the use of ANNs in hydrological modelling. Many studies explore potential forecasting of ANNs in the context of hydro-climatology, e.g., hourly discharge [*Deo and Thirumalaiah 2000*], daily discharge [*Phien and Danh 1997; Brikundavyi et al. 2002; Cigizoglu 2004*], monthly discharge [*Phien and Siang 1993; Salas et al.2000*] and seasonal discharge [*Uvo et al. 2000*], as well as hourly rainfall [*Olsson et al. 2004*] and monthly rainfall [*Freiwan and Cigizoglu 2005*]. Successful achievements were obtained through their studies implying that ANN can provide good forecast when network types, training methods and data handling techniques are identified.

Within the context of hydro-climatology, ANN is used here to develop models to forecast rainfall and discharge over the VCH based on SST and other meteorological variables available, as done in **paper III** and the **technical report**.

The best accuracy was achieved when using a multi-layer, feed-forward neural network. The ANN is composed of three layers, one output layer containing one neuron, one input layer containing as many neurons as the number of input variables, and one hidden layer. The number of the neurons in the hidden layer was chosen through test runs with a small number to begin with and gradually increasing the network size. The activation functions in the neurons of the hidden layer are hyperbolic tangents. In the output layer hyperbolic tangents are used for discharge forecasts, while linear tangents are used for rainfall forecasts.

The mathematical expression of the hyperbolic tangent sigmoid transfer function is as follows:

$$a = \frac{e^n - e^{-n}}{e^n + e^{-n}}$$

The linear transfer function is given by a=n, where n is the input and a is the output

The scaled conjugate algorithm is used for training processes. It is a sufficiently accurate and robust technique to train the network [*Moller 1993*]. He developed the scaled conjugate algorithm, which applies quadratic approximation to the error in a neighbourhood of the current point. Super linear convergence is obtained by using a step size scaling mechanism, which makes the algorithm faster than standard back propagation algorithms. The iteration is finished when a given minimum error is reached, or a given number of training epochs is completed. In the present work associated with ANN training, a stopping rule was adopted corresponding to an error between one interaction and the next as small as 0.001, or after 300 epochs. In this way overfitting can be avoided so that a satisfactory generalization can be reached.

3.4 Cross-validation

This section is mainly based on studies of cross-validation technique presented by *Graham et al. [1987a, b]* and *Derks et al. [1996]*.

Cross-validation is a method used in models in which the data set is divided into N subsets. Each time one of the N subsets is used as a test set or a validation set, and the other N-1 subsets are used to construct a training set, as displayed in Fig. 14. The training subsets are used in the model to estimate the test set, and the method is repeated N times to estimate all omitted subsets in the dataset. Every subset is used as a test set exactly once, and as element in the training set precisely N-1 times. The average error across all N trials is providing unbiased measures of the generalization error [*Graham et al. 1987a, b; Derks et al. 1996*]. The variance of the resulting estimate is reduced as N is increased. The disadvantage of this method is that the training algorithm has to be rerun N times to make an evaluation, which means that it can be time consuming.
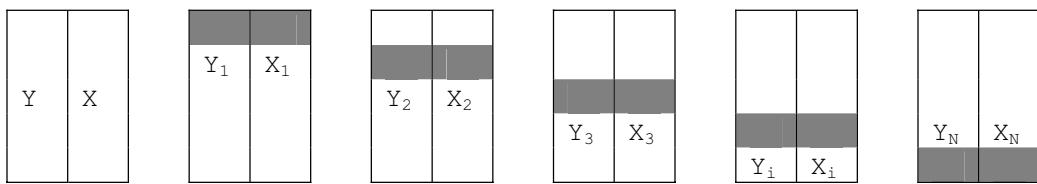
Figure 14 Subdivision of the dataset into subsets of validation (shading) and calibration (white) for cross-validation (adapted from *Derks et al.1996*)

Leave-one-out cross validation is used to develop the models applied in **paper II** and **paper III**. It consists of removing one value at a time from the time series that will be used for the development of the model and then estimate the missing value using the constructed model. The number of repeating model reconstructions is the same as

the number of omitted values. This version of cross-validation was chosen due to the small number of events in the available data series.

4. Summary of Results

4.1 The influence of SST on precipitation

Rainfall variations throughout the rainy season over the VCH are mainly influenced by the SASM and the topography of the region. An active phase of the SASM can bring rainfall, and a break phase can cause lack of rain. Fluctuations of the SASM are related to changes of SST over the Pacific and Indian oceans through large-scale circulation patterns.

The relationship between monthly SST in the tropical Pacific and the Indian oceans and monthly precipitation throughout the rainy season (April to November) over the VCH has been investigated by means of singular value decomposition. The results were obtained from the first modes (or the leading mode) of SVD. The assessment of the analyses was based on correlation coefficients and also supported by the NSC defined by *Wallace et al. [1993]*. The results obtained from SVD can be seen in detail in **paper I**, in which different relationships between the tropical Pacific and the Indian Ocean SST and precipitation patterns over the VCH during the different months of the rainy season were determined. The simultaneous analysis shows that rainfall variations over the VCH are most sensitive to SST changes in April, October and November. The SST changes can significantly influence the monsoon onset and withdrawal during the early and late rainy seasons, respectively. In June to September, the analyses reveal that rainfall variations over the VCH are weakly correlated with the SST anomalies over both oceans. The time-lagged relationships between precipitation and SST revealed that the Pacific SST is well correlated with the rainfall one to three months in advance throughout the rainy season, except in August. For the Indian Ocean, significant time-lagged relationships (one and two months) were found between the Indian Ocean SST and the VCH precipitation in October and November. Especially in October and November, high time-lagged correlations between precipitation over the VCH and SST patterns in both oceans were observed.

Figure 15a shows the correlations between precipitation over the VCH and Pacific and Indian Ocean SST anomalies in April, reflecting the transition from the dry to the wet season. The SST anomaly in the central equatorial Pacific, representative of ENSO, is negatively correlated with precipitation over the VCH, indicating that an El Niño (La Niña) event would imply a decrease (increase) in precipitation over most of the VCH. On the other hand, SST in the equatorial eastern and south-western Indian Ocean is positively correlated with precipitation in the northern part of the VCH at that month. However, results show that SST in the Pacific plays a more important role for rainfall variations over the VCH in April than SST in the Indian Ocean, as expressed by NSC values of 0.25 and 0.17, respectively. ENSO events affect rainfall over the VCH

through variation of the convective activity over the north-western Pacific [*Yoo et al. 2004*]. Thus, what the heterogeneous correlation maps for April shows is an increase of rainfall over the VCH associated with positive (negative) SST anomalies in the north-western (central equatorial) Pacific. This is in agreement with *Xie et al. [1998]* and *Zhang et al. [2004],* who stated that warm (cold) SST in the central to equatorial eastern, representative of El Niño (La Niña), suppresses (enhances) convection corresponding to cold (warm) SST in the north western Pacific and the equatorial eastern Indian Ocean. The convection then affects the SASM circulation, subsequently influencing the rainfall over the VCH.

In October (Fig. 15b), the central equatorial Pacific SST is highly negatively correlated with precipitation over the VCH (NSC = 0.3). The equatorial eastern Indian Ocean SST is positively correlated with precipitation over the VCH (NSC = 0.23). In this month, the precipitation over the VCH is associated with SASM withdrawal [*Wang and Wu 1997*] and deep convective activities over the eastern Indian Ocean [*Goswami and Shukla 1984; Qian and Lee 2000*]. A possible physical mechanism associated to what is shown in Fig. 15b is that warm (cold) SST in the central to eastern equatorial Pacific highly enhances cold (warm) SST in the eastern Indian Ocean through air-sea interactions, and then warm SST in the equatorial eastern Indian Ocean enhances the convective rain band over the VCH.

Figure 15c shows analyses from November, late in the rainy season. Precipitation over the VCH is highly positively correlated with the north-western Pacific SST (NSC = 0.28) and equatorial eastern Indian Ocean SST (NSC = 0.22). During this month, the south-westerly wind is already replaced by a north-easterly wind, and the precipitation over the VCH is still governed by the convective activities [*Goswami and Shukla 1984; Qian and Lee 2000*]. The heterogeneous correlation maps for November show that warm SST in the north-western Pacific and eastern Indian Oceans is associated with an increased rainfall over the VCH in agreement with *Qian and Lee [2000].* They revealed that warm SST in the north-western Pacific and eastern Indian oceans plays a major role in enhancing the convective rainfall over the VCH. The convective rainfall over the VCH ends in November.

The precipitation in April is highly negatively correlated with SST in the central to eastern tropical Pacific (representative of ENSO), and positively correlated with SST in the north-western Pacific from one to three months in advance (Fig. 16) with NSC values around 0.3. A possible physical mechanism to what is shown in Fig.16 is that the warm(cold) SST in central to eastern tropical Pacific corresponding to cold (warm) SST in north-western Pacific may delay (advance) the onset of the SASM, subsequently reduce (increase) the rainfall over the VCH. In other words, ENSO has a strong long-term influence on the onset of the rainy season over the VCH expressing the advance or the delay of the SASM over the Indochina Peninsula.

Figure 17a shows the lagged relationships between precipitation in October over the VCH and SST in the Pacific and Indian oceans up to three months in advance. The precipitation over the VCH is negatively (positively) correlated with SST in the central equatorial (western) Pacific (Fig. 17a$_1$) and positively correlated with SST in regions around the equatorial Indian Ocean (Fig. 17a$_2$). The high lagged correlation between SST in the Pacific and precipitation over the VCH from one to three months in advance, corresponding NSC values are 0.28, 0.23 and 0.21, respectively, are displayed in Fig. 17a$_1$. On the other hand, high correlation between precipitation and SST patterns in the equatorial eastern Indian Ocean, the NSC is 0.21, can be found one month in advance (Fig. 17a$_2$). The rainfall variation over the VCH in October is associated with deep convection, withdrawal of the SASM, and the Indian Ocean ITCZ [*Goswami and Shukla 1984; Wang and Wu 1997*; *Qian and Lee 2000*]. A reasonable physical mechanism related to what is shown in Fig. 17a is that the onset of ENSO influences rainfall over the VCH from one to three months in advance by influencing the variations of the SASM. On the other hand, warm (cold) SST in September in the eastern Indian Ocean can enhance (suppress) convective activities and the ITCZ movement over the southern Indochina Peninsula, subsequently increase (reduce) rainfall over the VCH in October.

Precipitation in November is positively (negatively) correlated to SST in the western (central tropical) Pacific (Fig. 17b$_1$), and positively correlated to SST in the equatorial eastern Indian Ocean (Fig. 17b$_2$) up to three months in advance. The rainfall in this month is related to convective activities in the equatorial eastern Indian Ocean and the north-western Pacific [*Qian and Lee 2000; Yoo et al. 2004*]. A possible physical mechanism associated to the heterogeneous maps shown in Fig. 17b is that a warm (cold) SST in eastern Indian Ocean and north-western Pacific can motivate (suppress) convective activities in relation to heavy rainfall over the VCH at the end of the rainy season. It is apparent that the SST pattern variations over the equatorial eastern Indian Ocean and the north-western Pacific have a long-term influence on precipitation over the VCH.

The relationships identified between monthly precipitation and monthly SST in the Pacific and Indian oceans may provide the basic of a predictive scheme. Establishment of such a scheme would require further analysis of the skill that can be achieved in prediction of precipitation over the VCH. The results obtained in **paper I** has been used toward the development of models for monthly precipitation forecast, eventually for use in agricultural planning and early drought warning in the central highlands -Vietnam.
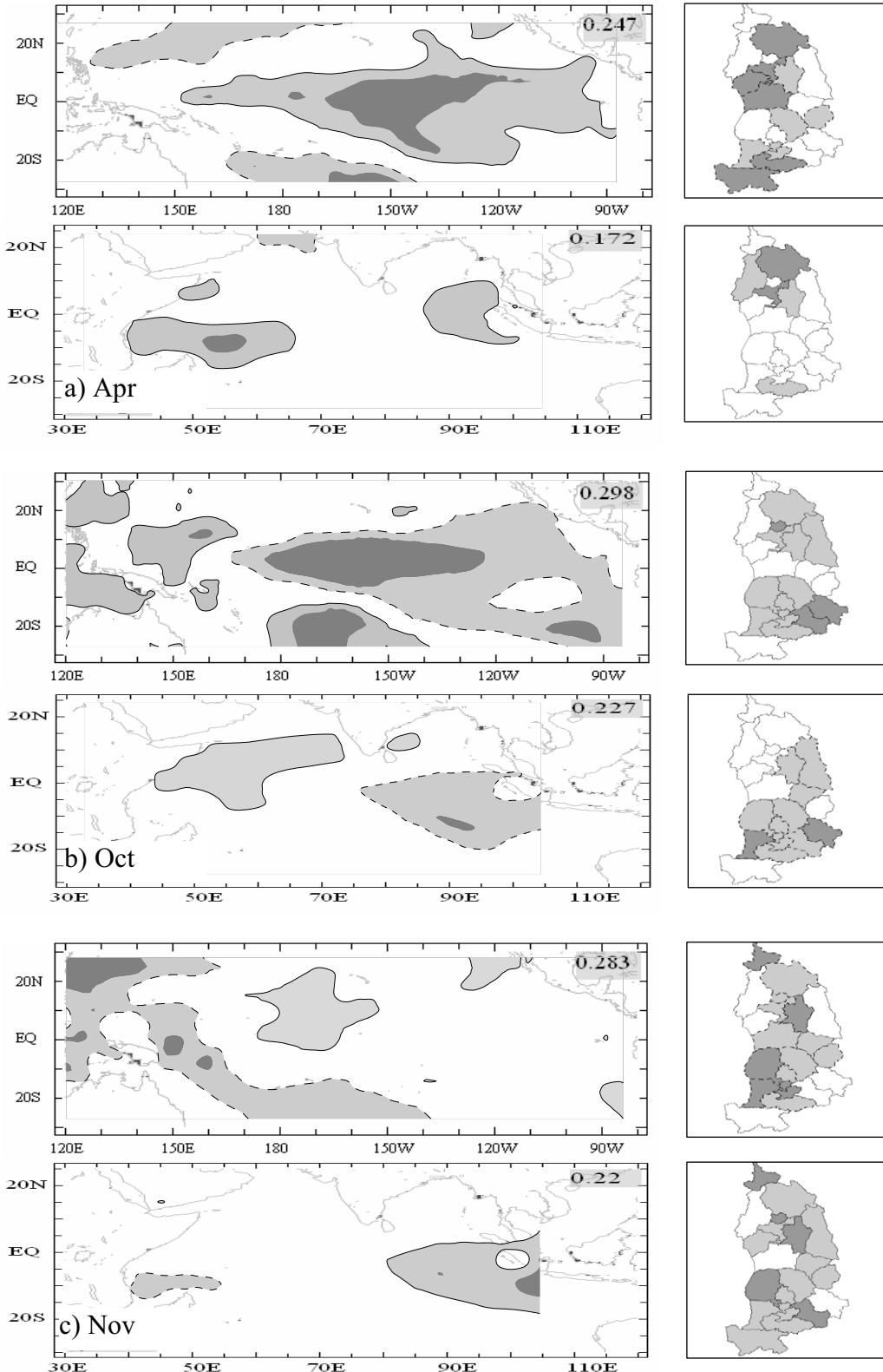
Figure 15 Heterogeneous correlation map for the first mode in the SVD expansion for monthly Pacific SST and precipitation (up panel), and Indian Ocean SST and precipitation (lower panel). The NSC value is presented on top right of left panel. Solid lines represent positive correlation coefficients and dashed lines, negative ones. Light and dark shading show correlation coefficient above 0.4 and 0.6 (below -0.4 and -0.6), respectively.

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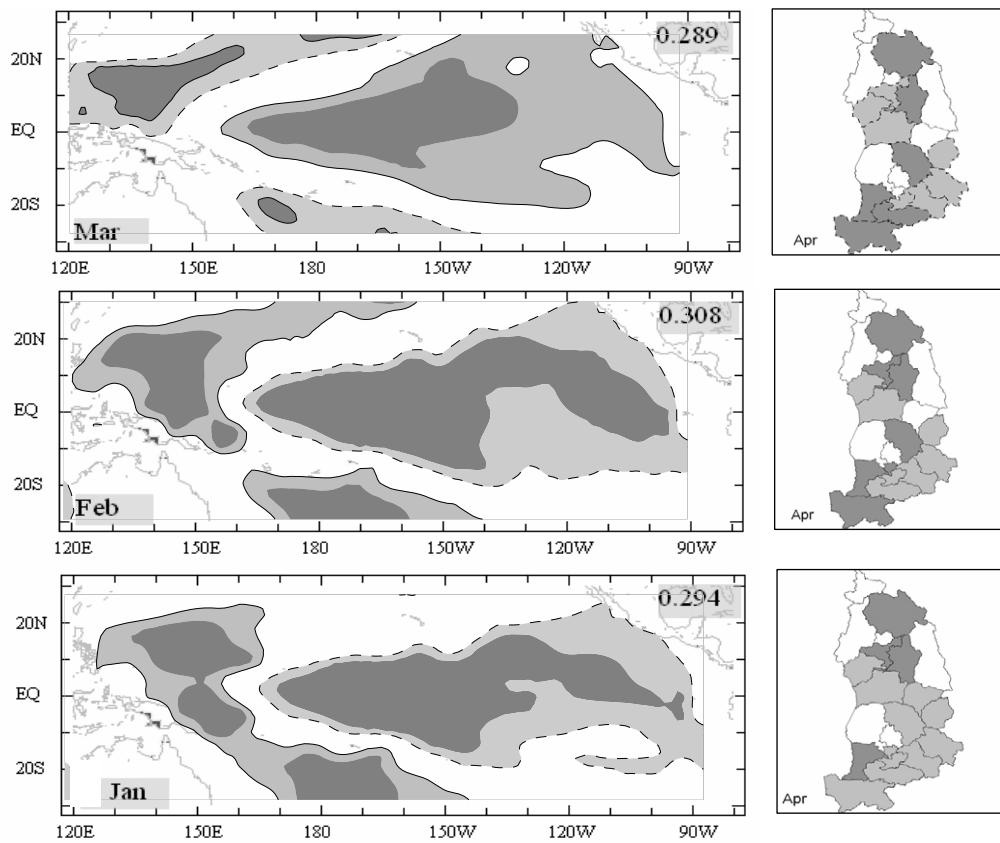
Figure 16 Heterogeneous correlation map for the first mode in the SVD expansion for precipitation (right panels) and preceding monthly Pacific SST (left panels). The NSC value is presented on top right of left panel. Solid lines represent positive correlation coefficients and dashed lines, negative ones. Light and dark shading show correlation coefficient above 0.4 and 0.6 (below -0.4 and -0.6), respectively.

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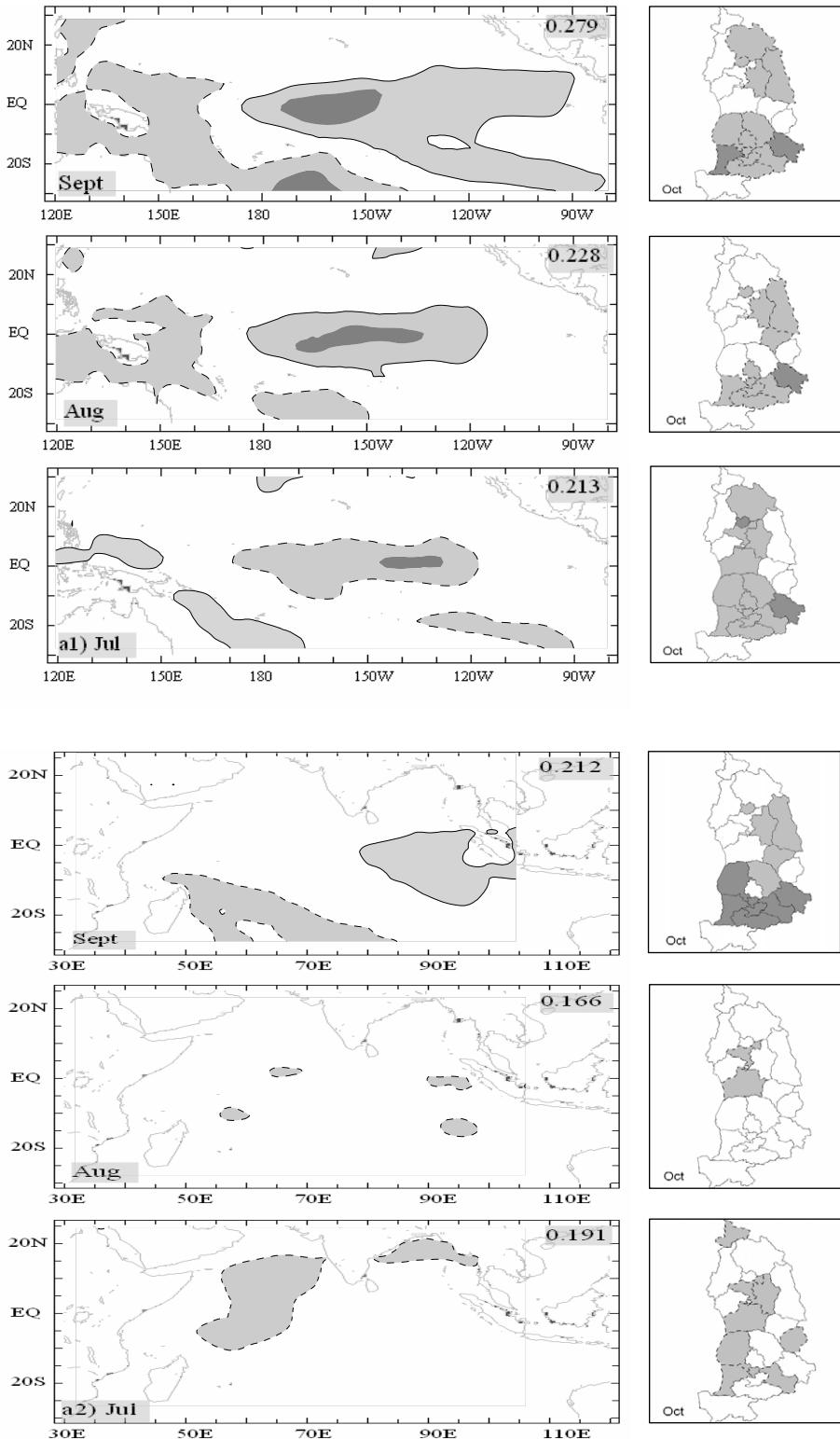
Figure 17 Heterogeneous correlation map for the first mode in the SVD expansion for precipitation (right panels) and preceding monthly Pacific and Indian Ocean SST (left panels). The NSC value is presented on top right of left panel. Solid lines represent positive correlation coefficients and dashed lines, negative ones. Light and dark shading show correlation coefficient above 0.4 and 0.6(below -0.4 and -0.6), respectively.

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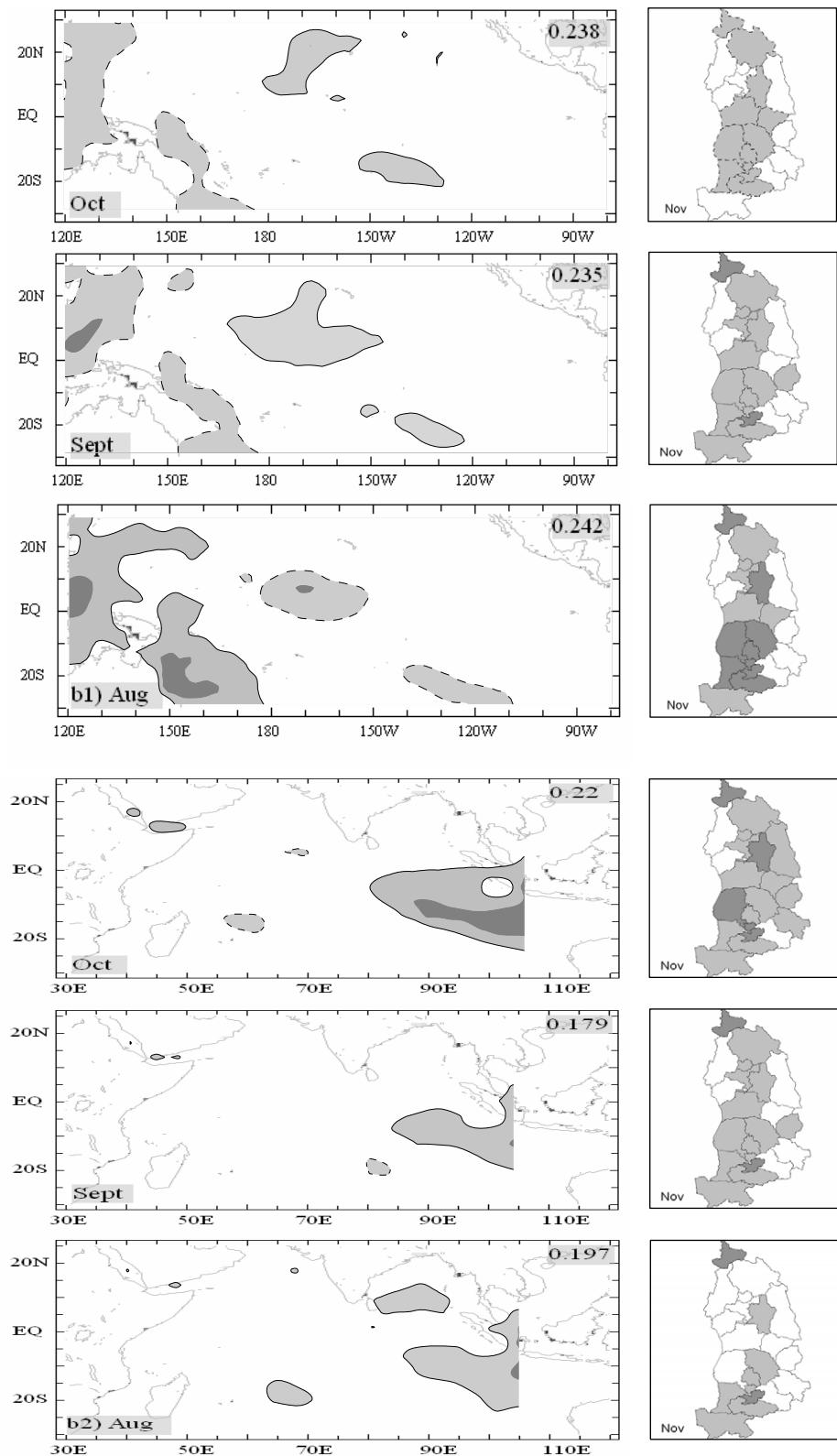
Figure 17 *(Continued)*

4.2 Rainfall forecasting

4.2.1 Linear model

Improvement of the monthly rainfall forecast over the Vietnamese central highlands may contribute significantly to water resources planning and management in terms of, e.g., improvement of reservoir operation, agricultural practice and, in particular, the mitigation of drought effects. Motivated by the strong relationships between precipitation over the VCH and SST in the Pacific and Indian oceans up to three months in advance using SVD as demonstrated in **paper I**, predictive statistical models are developed in **paper II** using CCA to forecast monthly rainfall for 21 selected sites over the VCH.

Empirical orthogonal functions (EOF) can be used for reducing the dimensionality in a dataset while maintaining most of its variance. EOF is used to describe the variance in the SST (predictor) and precipitation (predictand) datasets before applying CCA in order to reduce the noise from the original data set. After many tests, the first two EOF modes from the predictor and predictand were kept for the development of the CCA models. The best results of forecasting from EOF express the evolution of the dominant modes of individual months using separate oceans. The cross-validation method was used as a technique for validating the CCA model. The quality of the forecast models is tested by examining the correlation coefficients between observed and estimated time series of precipitation by cross-validation of the CCA model.

In general, the results obtained from the models using individual ocean SST vary significantly, temporally as well as spatially, during the rainy season. The best forecasts according to the cross-validation of the models were obtained based on SST two months in advance for rainfall in April and November, as presented in Table 2. It is found that February SST in the equatorial central to eastern Pacific Ocean, representative of the ENSO phenomenon, is a key factor for rainfall forecast in the early rainy season (April) and that September SST in the equatorial eastern Indian Ocean may be a good predictor for rainfall at the end of the rainy season (November).

Results obtained for May to October do not present the same quality as those for the early and late rainy season, however, some interesting aspects were found by the CCA models (see details in Table 1 of **paper II** in the appendix) because the rainfall over the VCH is influenced by local climatic patterns as well as the large-scale circulation governing the prevailing winds during the year. The local climatic patterns are mainly formed by the prevailing monsoon in combination with the topographical conditions in the region. Moreover, during the main rainy season, heavy rainfall over the VCH is primarily caused by cyclones, typhoons and other disturbances associated with complex atmospheric large-scale circulations, so in this period few significant results could be obtained from the models based on only SST.

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Table2 Correlation coefficients between standardized observed and estimated precipitation are obtained by cross-validation models. *, ** indicate correlation significant at > 95% and > 99%, respectively. N, C, S indicate stations in the north, centre and south of the region, respectively.

SST over	Pacific	Indian	SST over	Pacific	Indian
Precipitation	Apr	Nov	Precipitation	Apr	Nov
SST in	Feb	Sep	SST in	Feb	Sep
Dakglei(N)	0.21	0.48*	Bandon(S)	0.09	0.53*
Dakto(N)	0.63**	0.64**	Buonho(S)	0.60**	0.52*
Trungnghia(N)	0.17	-0.17	Buonmathuot(S)	-0.46*	0.10
Kontum(N)	0.07	0.61**	Krongbuk(S)	0.41	0.23
Pmre(C)	0.59**	0.69**	Eakmat(S)	0.58**	0.47*
Pleiku(C)	0.60**	0.60**	M'drak(S)	0.37	0.29
Ankhe(C)	0.12	0.26	Cau14(S)	0.53*	0.50*
Chupong(C)	0.52*	0.31	Giangson(S)	0.39	0.49*
Chuse(C)	0.51*	0.60**	Ducxuyen(S)	0.66**	0.43
Ayunpa(C)	0.31	0.45*	Daknong(S)	0.67**	0.39
Krongpa(C)	0.63**	0.37			

Figure 18 shows time series of standardized observed and forecasted precipitation in April at some sites, obtained from the CCA cross-validation using Pacific Ocean SST in February as predictor. The correlation coefficient varies from 0.51 to 0.67. In general, the model can reproduce well the variation in the sign of a monthly rainfall anomaly, however, intensities are generally underestimated. The model generates better forecast for monthly rainfall anomalies during the 1990s for most sites of the VCH, but it remarkably underestimates the extreme rainfall anomalies in 1996 and 1997 for Pmre (Fig. 18b), in 1997 for Cau14 (Fig. 18i), Ducxuyen (Fig. 18j) and Daknong (Fig. 18k), and in 1999 for Chupong (Fig. 18d). The model is able to forecast well rainfall anomalies during the early to middle 1990s for the sites of Cau14, Ducxuyen and Daknong in the southern VCH and from the middle to late 1990s for Dakto in the northern and Pleiku and Chupong in the central VCH. For most of the cases, the model cannot reproduce well the intensity of the extreme precipitation anomalies despite they are mainly associated to ENSO events (e.g. 1987, 1992 and 1998). However, it is clear that the model, when using SST over the Pacific as predictor, is able to indicate dry or wet conditions at the beginning of the rainy season two months in advance. This information is highly valuable for decision-makers in relation to agricultural management, among others.

In Figure 19, the time series of standardized observed and forecasted precipitation in November at some sites, obtained from the CCA cross-validation using Indian Ocean SST in September as predictor, are presented. The eight selected stations include two sites in the northern (Dakto, Komtum shown in Figs. 19a, b), three in the central (Pmre, Pleiku and Chuse in Figs. 19c, d, e) and three in the southern VCH (Bandon, Buonho and Cau14 shown in Figs. 19f, g, h). The best correlation coefficient between observed and estimated precipitation is 0.69 at Pmre (Fig. 19c) and the worst is 0.50 at Cau14 (Fig. 19h). Like for the early rainy season, the model is also able to indicate wet or dry conditions at the end of the rainy season, but not its intensity. This

information, however, is valuable for water management given that it is provided two months before the end of the rainy season.
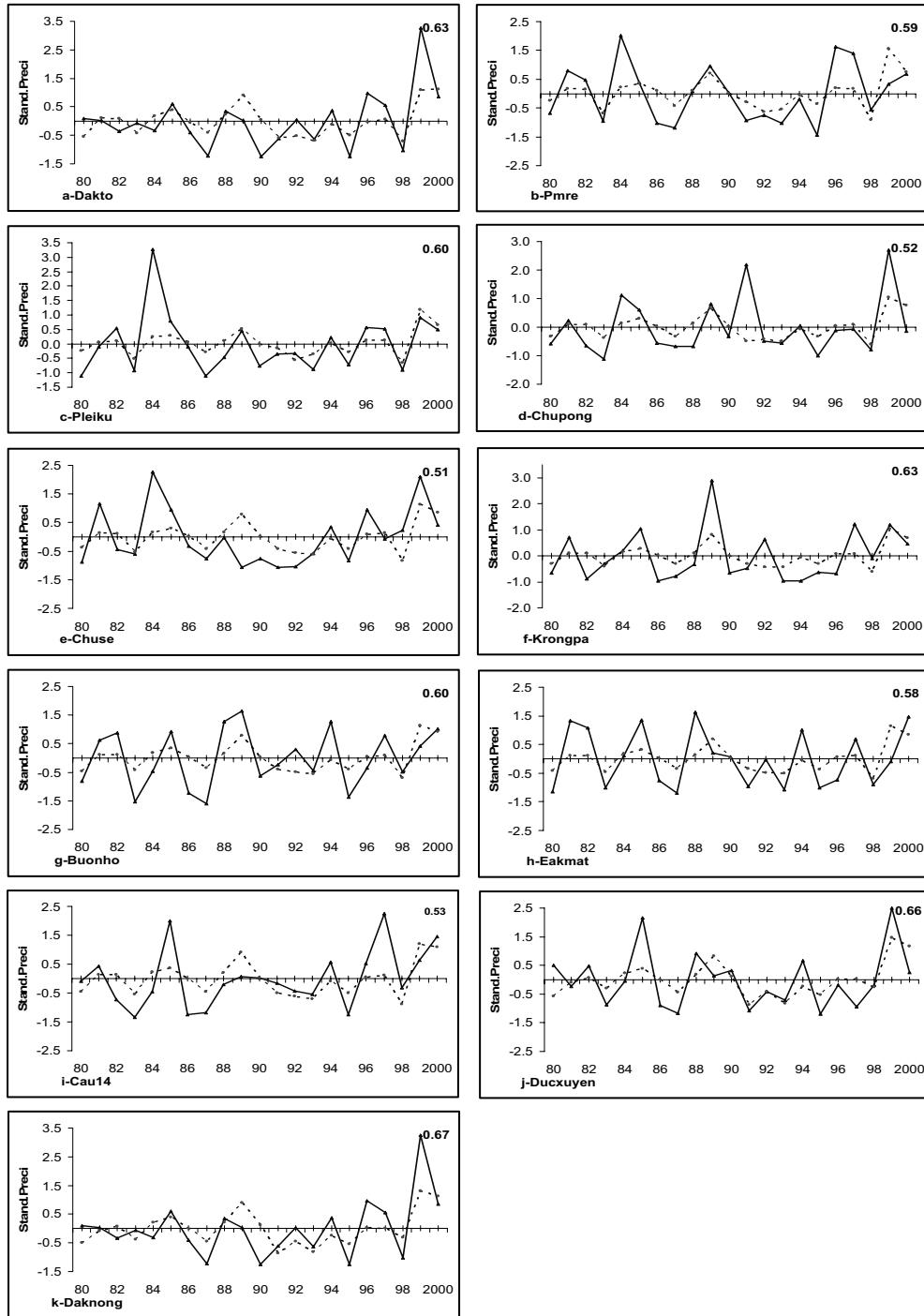
Figure 18 The time series of standardized observed (solid line) and estimated (dashed line) precipitation in April obtained from cross-validation model using SST in the Pacific Ocean as predictor. The correlation coefficients between two time series presented on the top right of each graph are statistically significant at levels >95%.
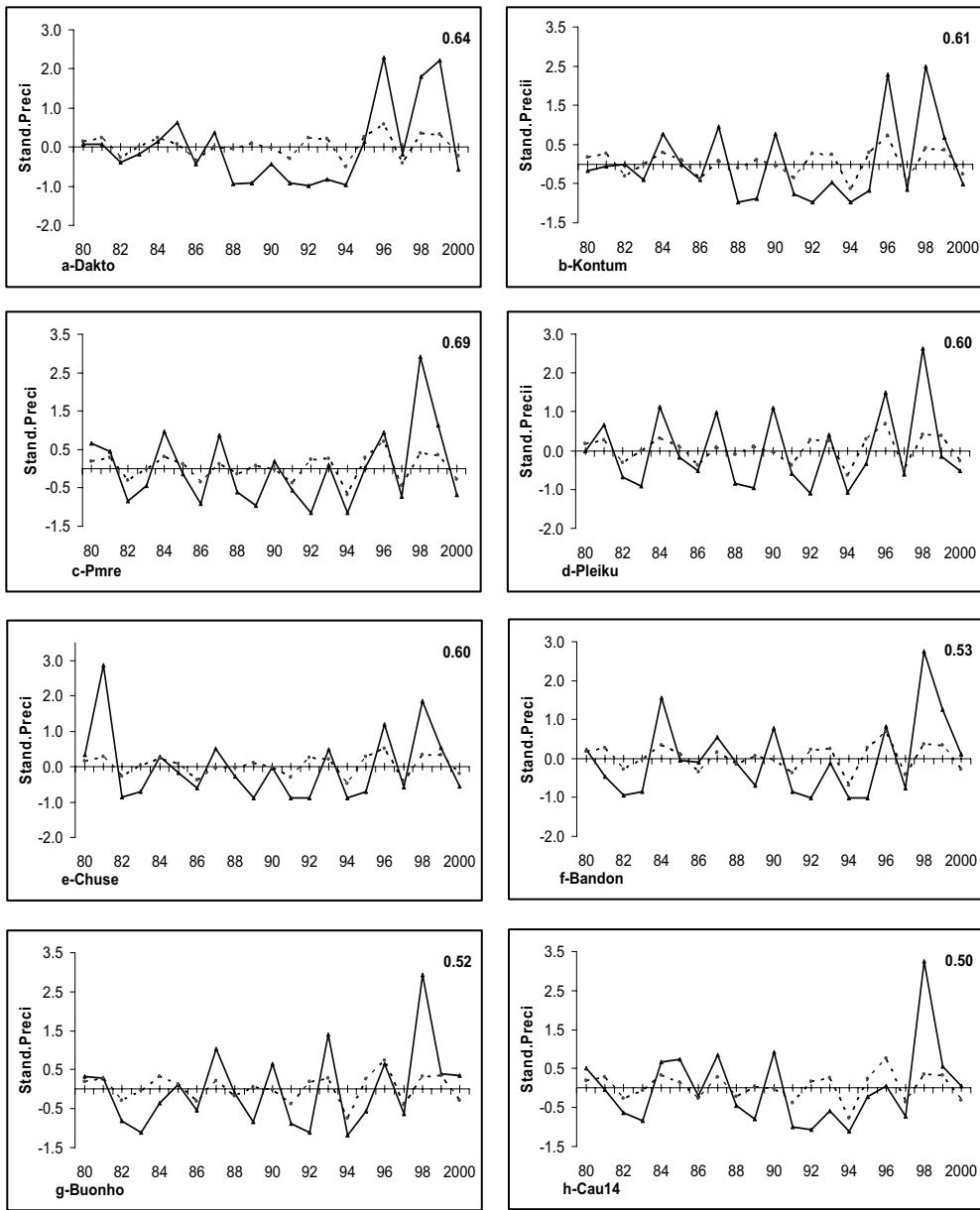
Figure 19 The time series of standardized observed (solid line) and estimated (dashed line) precipitation in November obtained from cross-validation model using SST in the Indian Ocean as predictor. The correlation coefficients between two time series presented on the top right of each graph are statistically significant at levels >95%.

To examine the temporal and spatial evolution in the predictor field that gives the best forecast skill to the predictand field, diagnoses were made by means of CCA techniques producing canonical predictor patterns or so-called g-maps. For the April rainfall forecast, the first two g-map modes explain maximally about 60% of the variance in April rainfall, as shown in Fig. 20, where the first mode accounts for 50%. The correlation coefficients in the first g-map mode imply that cold (warm) February SST in the equatorial central (north-western) Pacific contributes most to the April rainfall forecast. In other words, ENSO has a considerable long-term influence on the

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onset of the rainy season. The fact is that, during April, the heavy rainfall in the VCH is mainly caused by convective activities. The positive SST anomalies over the north-western and negative SST anomalies in the equatorial central to the eastern Pacific Ocean, representative of ENSO, could enhance the convective rainfall over the VCH. Thus, La Niña increases and El Niño decreases precipitation over the VCH. This pattern was also suggested by, e.g., *Zhang et al. [2002, 2004]* and in **paper I**.

Similar to the case in April, g-maps were obtained from CCA to determine which spatial distribution of SST in the Indian Ocean in September that might be most significant to November rainfall forecast over the VCH (in Fig. 21). The g-map obtained in this case shows that warm (cold) SST in the equatorial eastern (western) Indian Ocean is highly correlated with the canonical components that were used for forecasting rainfall, but it does not contribute much to the November rainfall forecast, which is in agreement with the findings in **paper I**. The first two g-map modes explain only 20% of total variance of the November rainfall. In November, the north-easterly winds replace the south-westerly ones. The rainfall over the VCH is associated with the convective rain band over the region, and moisture is fed to the rain band by positive SST anomalies in the equatorial eastern Indian Ocean *[Qian and Lee 2000]*.

The results obtained in **paper II** might lead to the conclusion that the variations of the rainfall over the VCH are not only associated with large-scale atmospheric and oceanic circulations but also depend on the local conditions, i.e. the complex topography combined with large-scale circulations. In particular, the two major mountain ranges in the north-eastern and south-eastern parts of the VCH (the elevation ranges from 1000 to 1500 m a.m.s.l) play an important role for the rainfall on the lee-side of the mountain ranges. The north-western Pacific and equatorial eastern Indian oceans feed the water vapour for the convection that causes precipitation over the VCH through large-scale atmospheric-oceanic circulations. The convection is triggered at the lee-side of the mountains forming the squall lines that generate the precipitation on the lee-side foot of the mountains [*Satomura 2000*]. This partially explains the spatial rainfall variations over the VCH, and also the spatial variability of model skills.

The rainfall at the early and late rainy season can be forecasted two months in advance by means of CCA. The models using SST as predictors cannot forecast the intensities, especially catching the peak of the rainfall anomalies, but they clearly indicate the signal of a prolonged or shortened season. This information is important and supportive for water resources management and crop patterns decision-making. However, the forecasting results obtained in **paper II** imply that the true forecast skills need to be further investigated to improve the quality of the rainfall forecast using other approaches.
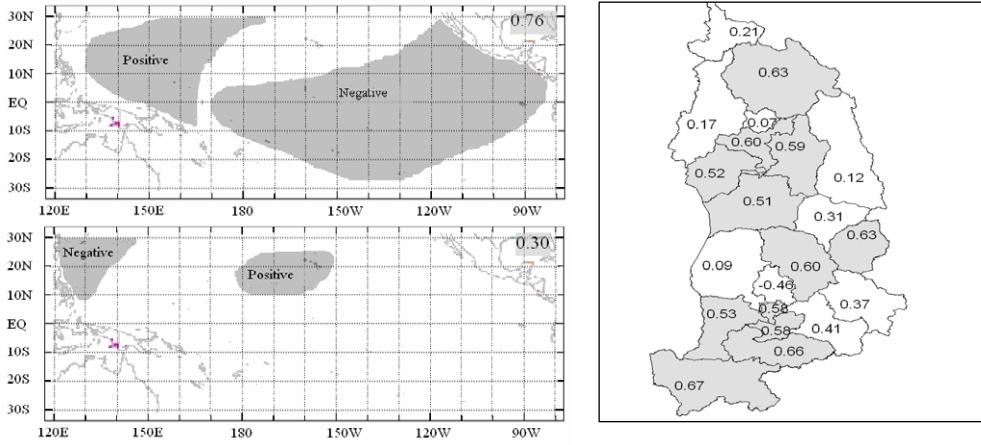
Figure 20 The first (upper left panel) and second (lower left panel) mode of canonical predictor maps associated with April rainfall forecast skill based on February SST in the Pacific Ocean. The shading shows the SST areas that contribute most to the forecast. The correlation coefficient between canonical components of predictor and predictand is shown on the top right of each left figure. The right panel indicates the correlation coefficients between standardized observed and estimated precipitation obtained from all modes of cross-validation models. The correlation coefficients above 0.45 and 0.55 are significant at levels > 95% and > 99%, respectively.
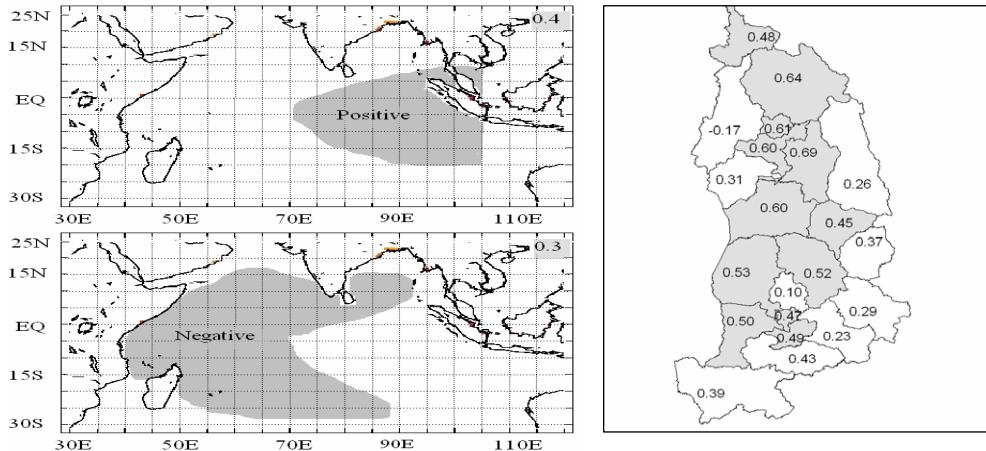
Figure 21 The first (upper left panel) and second (lower left panel) mode of canonical predictor maps associated with November rainfall forecast skill based on September SST in the Indian Ocean. The shading shows the SST areas that contribute most to the forecast. The correlation coefficient between canonical components of predictor and predictand is shown on the top right of each left figure. The right panel indicates the correlation coefficients between standardized observed and estimated precipitation obtained from all modes of cross-validation models. The correlation coefficients above 0.45 and 0.55 are significant at levels > 95% and > 99%, respectively.

4.2.2 Nonlinear model

Based on the persistent findings in **paper I** and **paper II** that the rainfall at the early rainy season over the VCH can be forecasted but the quality of the forecasts needs to be improved by further efforts, the ANN approach was used to forecast rainfall at 21 selected sites over the VCH. The ANN seems to be a suitable technique for the rainfall forecast at most of the sites over the VCH. Cross-validation was used to check the

quality of the ANN models due to the relative short data series. The accuracy of the trained networks in forecasting varies from site to site. The quality of the forecast is expressed by the correlation coefficient between observed and estimated time series, and the root mean squared error value.

In general, forecast skills are better for sites located in the southern VCH reflecting that the southern parts are more clearly influenced by the large-scale circulation than those in the northern parts, corresponding to the findings in **paper I** and **paper II**. A large improvement of the forecasts is obtained when the input to the models contains both SST and local climatic variables. The poorest results are obtained from the models for sites where no meteorological variables are available to be used as input and where rainfall regimes are mainly characterized by the local climate.

Table 3 presents the results obtained from the ANN cross-validation models for rainfall forecast at 21 selected, well-spread sites over the VCH. April rainfall is forecasted by using as input the January, February and March SST first EOF mode, and March air temperature, humidity and wind speed from the different stations. In general, the quality of the forecast results varies spatially and improves southward.

Table 3 Summary of the results obtained from the ANN models for forecasting April rainfall at all sites available over the VCH. Corr.coeff. is the correlation coefficient between the time series of scaled standardized observed and estimated rainfall obtained from the cross-validation models. RMSE is the root mean squared errors for the whole time series. SST denotes sea surface temperature in the Pacific, and H, T, W and P indicate humidity, air temperature, wind speed and precipitation, respectively. The subscript shows the number of months prior to the rainfall forecast in April.

Stations	Input to network	Corr.coeff	RMSE in range [-0.9 ,0.9]
Dakto(N)	$SST_{1,2,3}$	0.56	0.31
Dakglei(N)	$SST_{1,2,3}, H_1$	0.47	0.36
Trungnghia(N)	$SST_{1,2,3}$	0.32	0.45
Kontum(N)	$SST_{1,2,3}, H_1$	0.47	0.37
Pmre(C)	$SST_{1,2,3}, H_1, T_1$	0.58	0.31
Pleiku(C)	$SST_{1,2,3}, H_1, T_1$	0.66	0.20
Ankhe(C)	SST_2	0.13	0.30
Chupong(C)	$SST_{1,2,3}, P_1, T_1$	0.64	0.26
Chuse(C)	$SST_{1,2,3}, H_1, T_1, W_1$	0.63	0.36
Ayunpa(C)	$SST_{1,2,3}, H_1, T_1$	0.77	0.29
Krongpa(C)	$SST_{1,2,3}, H_1$	0.71	0.22
Bandon(S)	SST_2	0.24	0.29
Buonho(S)	$SST_{1,2,3}, W_1$	0.54	0.47
Buonmathuot(S)	SST_2	-0.83	0.49
Krongbuk(S)	SST_2, H_1	0.43	0.33
M'drak(S)	$SST_{1,2,3}, P_1, T_1, W_1$	0.84	0.21
Eakmat(S)	$SST_{1,2,3}, T_1$	0.68	0.40
Giangson(S)	$SST_{1,2,3}, H_1, W_1$	0.55	0.31
Cau14(S)	SST_2, P_1	0.45	0.35
Ducxuyen(S)	$SST_{1,2,3}, H_1, T_1, W_1$	0.84	0.20
Daknong(S)	$SST_{1,2,3}, H_1, T_1, W_1$	0.84	0.15

Good results were generally obtained for sites in the southern VCH. This area comprises a complex terrain with mountain ranges and a flat plateau. The highest correlation coefficient (0.84) was found for Daknong, Ducxuyen and M'drak with RMSE values about 0.2. The good results obtained for these sites are in accordance with results obtained in **paper II**, where a strong relation was found between monthly rainfall and SST. The additional meteorological input variables associated to the local climate increased the correlation coefficient to 0.84, while exclusive use of meteorological variables as input decreased the correlation coefficient to 0.48 (Daknong), 0.43 (Ducxuyen) and 0.42 (M'drak). For the sites Eakmat, Giangson and Buonho, where meteorological variables at surrounding sites together with SST were used as input to the models, the correlation coefficient varies from 0.54 to 0.68 and the RMSE is approximately 0.4. Poor forecast results amongst the sites in the southern VCH were obtained for Bandon, Krongbuk, Cau14 and Buonmathuot due to the fact that rainfall at these sites might be mainly influenced by local climatic regimes such that the inputs to the models did not contain sufficient information about the target. These results emphasise the importance of having phenomena of different time and space scales represented in the ANN input.
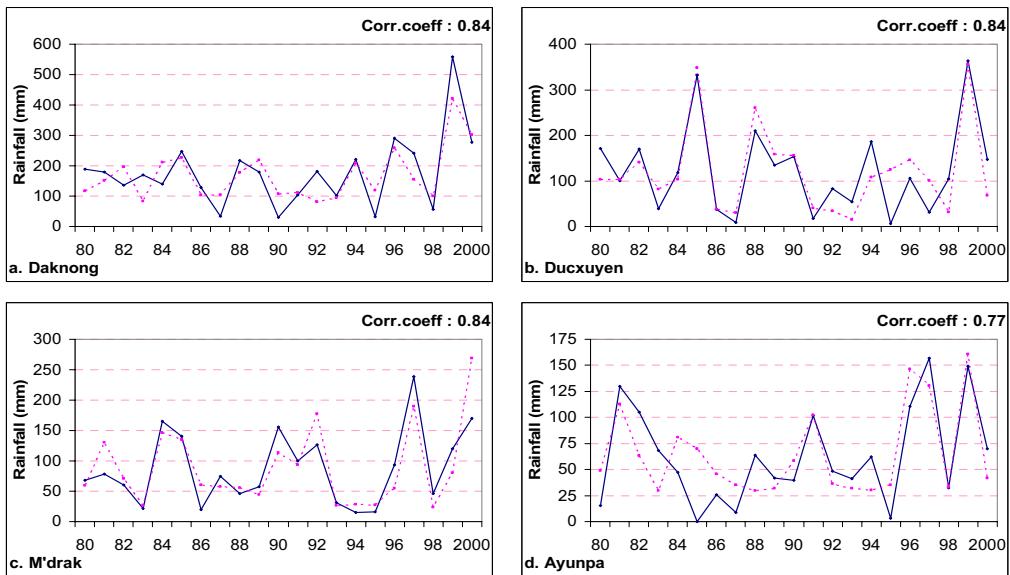
Figure 22 The time series of observed (solid line) and estimated rainfall (broken line) obtained from the cross-validation neural network models. The correlation coefficient between two time series is shown on the top right of each figure.

Best forecasts were produced for Daknong, Ducxuyen, M'drak in the VCH southern part and Ayunpa in the central part. Fig. 22 shows the time series of observed and estimated rainfall obtained from the cross-validation. In general, the models can reproduce well the variation and the intensity of the rainfall. For Daknong the model failed in estimating the sign of the rainfall in early 1980s and underestimated in 1999. The best ANN model performance is presented in Fig. 22b (Ducxuyen). The model

succeeds in estimating the positive extreme values but underestimates in 1993 and overestimates in 1995. For M'drak (Fig. 22c), the model underestimates the extreme value in 1997 and overestimates in 1981, 1992 and 2000. For Ayunpa (Fig. 22d), the model succeeds in estimating positive extreme values but it does not forecast well the mid of the 1980s.

The results obtained from ANN models for April rainfall forecast are considerably better than the forecast results obtained from the statistical models in **paper II** for the same month. This improvement is attributed to the ANN models in which the inputs to the models comprise SST in January, February and March, which are strongly correlated with April rainfall over the VCH as shown in **paper I**, and moreover some meteorological variables such as air temperature, humidity and wind speed in March that reflect local climatic.

4.3 Discharge forecasting

The nonlinear technique known as ANN was applied in the **technical report** to forecast discharge at three selected sites Bandon (in Srepok catchment), Kontum (in Sesan catchment) and Cungson (in Ba cathcment) over the VCH. The discharge data spanning the period January 1980 to December 2000 in which the data sets are divided into three subsets for model application, 13 years for calibration, next 3 years for checking and the last 5 years for validation, and it was used as the target of the ANN models. Among the inputs are SST in equatorial eastern Pacific (El Niño3) from 5°N-5°S; 150°W-90°W from the Comprehensive Ocean Atmosphere Data Set (COADS) [*Reynolds et al. 2002*] and extracted from the data library of the International Research Institute for Climate and Society - IRI. The data, available at a 2°x2^{o} lat-long grid point resolution, was transformed into a single time series by simple averaging. Moreover, meteorological data were also used as inputs to the models comprising air temperature, humidity, wind speed etc. The accuracy of the trained networks in forecasting varies site to site. The quality of the forecast is expressed by the correlation coefficient between observed and estimated time series, and the root mean squared error value.

The optimal design of an ANN is normally identified by trial and error tests. Hereby, the best accuracy was achieved when using a multi-layer feed-forward neural network. The ANN is constructed of three layers in terms of input-hidden-output layer, and the ANN structures are presented in Table 4. The output layer has one neuron, and the input layer contains as many neurons as the number of input variables. The number of the neurons in the hidden layer was chosen through test runs with a small number to begin with and gradually increasing the network size. A hyperbolic tangent sigmoid transfer function is used in the neurons of the hidden layer and in output layer

The results of the discharge forecast obtained from ANN models are presented in detail in Table 4. Two month lag SST in El Niño3 and one month lag humidity, air temperature and discharge are used as input to the models. In general, the models are

potentially able to forecast discharge at the sites in all three catchments of the VCH, the correlation coefficient ranging in interval of 0.78 to 0.88.

Table 4 Forecast results obtained from ANN models for three catchments over VCH. The inputs to the ANN models are: sea surface temperature (SST), humidity (H), air temperature (T), sunshine hours per month (n) and discharge (Q). The subscript shows the lag time prior to the forecast. The network structure information indicates the numbers of neurons in, respectively, the input, hidden andoutput layers, and RMSE stands for root mean squared error.

Site	Input to network	Network structure	Corr.coeff	RMSE
Bandon	SST_2, H_1,$T_{1\text{-max,min,mean}}$,n, Q_1	7-10-1	0.82	162.6
Kontum	SST_2, H_1, $T_{1\text{-max,min,mean}}$, Q_1	6-7-1	0.78	51.3
Cungson	SST_2, H_1, $T_{1\text{-max,min,mean}}$, Q_1	6-7-1	0.88	210

The results of discharge forecast are illustrated in Fig. 23. The scattering in the training periods indicates that the models tend to present well the discharge variability. The time series between observed and estimated values are presented in the right panels, and high correlation coefficients are obtained for all three sites, 0.82 for Bandon, 0.78 for Kontum, and 0.88 for Cungson. However, the models cannot catch the peaks of discharge, underestimating the discharge peak in 2000 at Bandon, in 1996 at Kontum, and in 1996, 1998 and 1999 at Cungson. This might be because the inputs to the models do not contain sufficiently valuable information about the peaks, which are primarily generated from the distribution of heavy rainfall and the characteristics of catchments. The fact is that most heavy rainfall events over the VCH are mainly caused by storms and typhoons that are complexly influenced by large-scale circulation.

The forecasting results for both rainfall and discharge will play a very significant role in early drought warning over the VCH. Good performance of models for both forecasts imply that drought indices generated from rainfall or discharge, or a combination, can be presented in advance and combined with real-time monitoring of other hydro-meteorological elements within the region, e.g., river discharge and water level in reservoirs, lakes and rivers. Hereby highly valuable information of future drought conditions can be made available to water managers and decision-makers that are responsible for preparing and implementing feasible, appropriate measures.
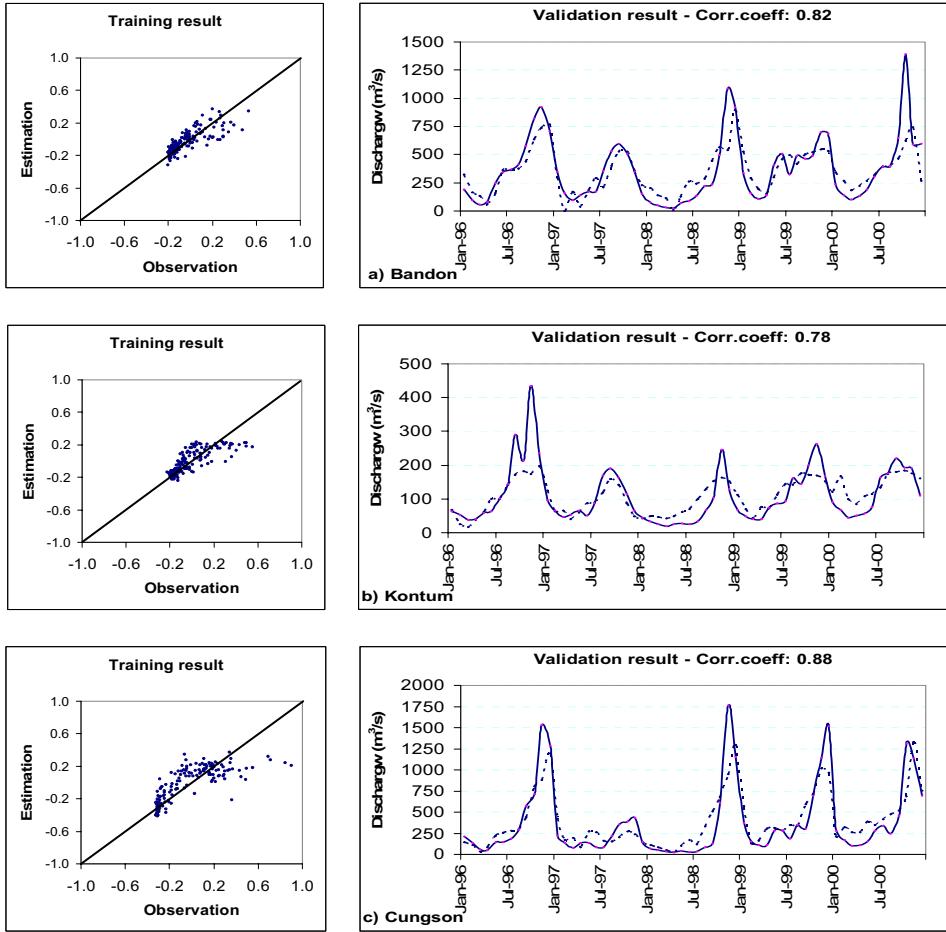
Figure 23 Forecast results for monthly discharge obtained from ANN models. Left panels show the training results. Right panels present time series of observed (solid) and estimated (dash) during the validation period for sites in three catchments.

4.4 Early Drought warning, mitigation and response

Drought is considered as a worldwide phenomenon affecting broad region and causing significant damages to both human lives and economic bases. Drought cannot be prevented but much can be done to reduce impacts on the environmental, social and economic sectors through preparedness and mitigation [*Wilhite et al. 2000*]. Rainfall over the VCH is plentiful but it is not well-distributed temporally, it focuses on some months in the rainy season accounting for approximately 80% of the annual amount. When water supply is scarce to meet the demand, only a few water users are directly affected, e.g., crops, livestock, but in the case of a severe and prolonged drought every water user is directly affected, and even sectors that do not use water may be affected due to the consequences of huge water shortage.

Primary roles of drought preparedness and mitigation are to identify drought definitions and handle issues related to drought impacts such as assessing vulnerability of the sectors exposed to drought, and recommending and preparing implementation of measures to mitigate effectively impacts due to water shortage. Drought can be defined in several ways; here the standardized precipitation index (SPI) defined by *McKee et al.*

[1993] and the surface water supply index (SWSI) developed by *Shafer and Dezman [1982]* are considered in relation to meteorological and hydrological droughts, respectively. It seems that both indices are potential drought indicators over the VCH by presenting drought conditions based on threshold categories from extreme wet to extreme dry conditions.

One of the most important components in drought mitigation is early warning; establishment of a drought monitoring system is essential and plays a very important role in early drought warning. A conceptual drought monitoring system in the central highlands - Vietnam is proposed to provide valuable information of a current drought occurrence or a possible drought event in future. Early drought warning would provide valuable information of the signal and trend of drought occurrences as well as their severity and duration to decision-makers and stakeholders such that they can prepare and take appropriate actions in due time to reduce impacts. Moreover, a drought response policy and corresponding organizational structures are suggested to efficiently implement a drought task force. Besides this, an implementation solution in terms of water resources management, science and technology promotion, training and education, communication and information enhancement (especially partnership arrangements) is identified to reinforce a drought task force dealing with impacts on affected sectors and enhancing sustainable development, as presented in the **technical report**.

4.4.1 Early warning

Early warning is one of the most important components in the context of preparedness and mitigation. It is conceptually comprised by a monitoring system, which has the ability to understand the response of droughts to climate variability, and to provide valuable information of the signal and trend of drought occurrence, severity, and duration to decision-makers and stakeholders to prepare and implement appropriate actions in due time to reduce impacts. As defined in *Demuth and Stahl [2001]* and *Wilhite et al. [2005]*, the drought monitoring system is generally responsible for:

-   Identifying drought management areas by subdividing the region into subregions sharing similar hydrological and climatological characteristics in which it is suitable to implement mitigation and response actions.

-   Monitoring drought occurrence and development by clearly determining the drought characteristics at various time scales, consecutively monitoring the drought evolution and identifying the trend of other meteorological and hydrological elements to enforce early drought warning.

-   Displaying drought distributions over the region, and determining as soon as possible the geographical positions where droughts are occurring.

-   Comparing and ranking the severity, duration, and extent of drought events to improve understanding about drought characteristics and help the water

managers and decision-makers in preparation and implementation of mitigation and response measures.

- Inventorying and prioritizing data quantity and quality from the current observation network to improve indictors that are able to reflect significant drought impacts on different sectors, and to deliver information effectively to the users.

Such a conceptual monitoring system design is proposed for application in the VCH, as displayed in Fig. 24, which would be composed by a network with representative gauging stations available over the region. The system receives data from relevant hydro-meteorological services by a host organization. The host organization then updates the data to the database to provide data to the professional models generating drought visualization in terms of drought indices and other supplemental elements on a website. From the website, managers or decision-makers can get sufficient information in relation to drought occurrence to prepare and implement appropriate measures to lessen potential impacts.
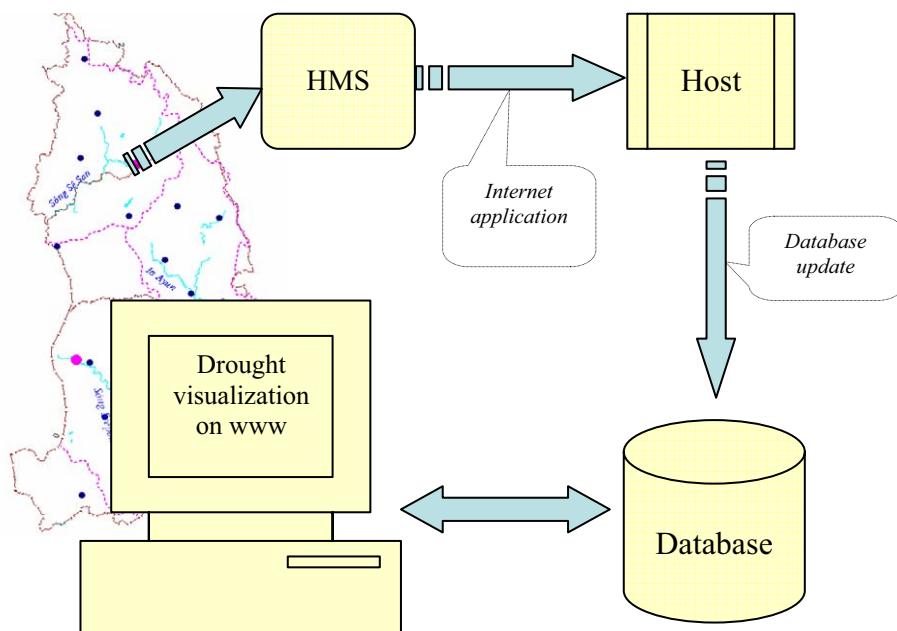
Figure 24 Proposal for drought monitoring system design (*Demuth and Stahl 2001*)

In order to monitor the occurrence and development of droughts efficiently and provide information on the strength and range of a drought for drought management, a robust system of indicators needs to be determined that is able to identify and diagnose anomalies in water availability. Multiple indicators need to be used to illustrate drought extension and severity, which would enhance the effectiveness in drought mitigation, since no single indicator can encompass the complexity of drought development [*Hisdal and Tallaksen 2000*]. Values that significantly departure from normal values in precipitation or a combination of precipitation and discharge, i.e. the standardized

precipitation index and the surface water supply index, are proposed to be used as key drought indicators in the VCH. Moreover, evapotranspiration (ET) and soil moisture (SM) need to be considered to supplement in drought occurrence identification. The combination of drought indicators based on analysing and forecasting meteorological and hydrological elements can provide decision-makers with sufficient information to understand the drought phenomenon and estimate its impacts on the environmental, economic and social sectors. For instance, when the development of a meteorological drought is being discussed, as identified by SPI values, the water managers should check for the trend of discharge, or SWSI values, and combine with ET and SM information in order to assess whether there is a significant risk of water shortage or not, followed by appropriate decisions in relation to implementation of feasible measures for drought mitigation and response.

4.4.2 Response policy

Drought response policy is a list of relevant actions to be taken in relation to drought mitigation, which are discussed and adopted by the highest legal competences. Regarding water resources management, the possible actions would be taken in combination with stakeholder seeking, information dissemination on encouragement or enforcement of water savings, restriction of certain uses, and focus on water resources conservation and environmental protection. From an institutional perspective, a drought committee needs to be appointed to address specific issues and to overcome the challenge of enhancing the collaboration between agencies, organizations and stakeholders. Different selections of measures to be taken would lead to different effectiveness in mitigation of multiple impacts on sectors [*Wilhite 1997*]. Only certain measures are feasible and potentially effective in a certain drought situation. Major elements in a drought policy have been described by *Grastang [2002], Wilhite [1991]* and *Garrote et al. [2005].* This information is available at the website of the U.S National Drought Mitigation Centre and found appropriate and feasible for application in Vietnam. The following scenario description from pre-alert to emergency situations is based on the above mentioned references.

When a pre-alert scenario is declared corresponding to moderate shortage of water supply and the initial stage of drought development, appropriate actions for the possibility of a drought need to be prepared. A drought assessment committee needs to be activated to evaluate the future scenarios and recommend appropriate actions for any scenarios that might happen in the future. The potential impacts on the environmental, economic and social sectors need to be clearly addressed, and conservation goals set. Moreover, the public must be informed in order to get accept of the measures that will be taken if the drought intensity increases. Another goal is to prepare the administration and the stakeholders for future actions they are supposed to implement. In this stage,

communication and awareness are the focal points, and non-structural measures are generally taken in order to reduce water demand, and to avoid an alert situation.

An alert scenario is declared when water supplies are significantly lower than the actual demand, and a severe drought occurs. There will probably be future impacts on the environmental, economic and social sectors if possible measures are not taken in this situation. The drought assessment committee should issue water shortage statements, inform the public on the problems and set more stringent conservation goals. The drought mitigation and response committee is activated to implement an educational effort aiming at voluntary conservation of all water uses combined with enforceable restrictions of non-essential water uses that do not affect drinking water, or water exchange between uses. The possible actions are taken in order to avoid a drought emergency situation by enacting water conservation policy and mobilizing additional water supplies. These measures are coercive to stakeholders, but in this situation water supply for high-priority uses should be guaranteed. This may cause conflicts between water users due to overruled user rights.

When there is a huge shortage of water supplies, which has impacts on the environmental, economic and social sectors, and water supply even for high-priority uses is not guaranteed if drought continues, an emergency situation is then declared. In this situation, strict measures are implemented to mitigate impacts and minimize the damage of drought. The drought assessment committee should inform the public through public media, including television, newspapers and local radio. The drought mitigation and response committee needs to implement measures immediately to reduce all water uses. The minimum water requirement for crops is a considerable priority and should be satisfied. The scarce water should be allocated fairly and equally in communities, with high priority to drinking water requirements. A maximum allowable usage should be set and water use should be charged with increasing rates per unit as the total use increases. The actions taken in the emergency case should be direct and restrictive due to their high economic and social cost, and some legal exceptional measures would be used in this situation such as subsidies and low-interest loans for water users, and aid programs should be activated to alleviate starvation and prevent diseases for residents living in the area affected by droughts.

4.4.3 Organisational structures

A proposal for a drought committee has been comprehensively presented by *Wilhite et al. [2000]* and *Grastang [2002]*. Additional information is found in *Wilhite et al. [1991]* and *Wilhite et al. [2005]*. The below proposal for the structure of a drought committee in Vietnam is based on these references.

A drought committee should be established to deal with diverse droughts following adopted legal guidelines. During drought occurrence, the drought committee should work closely with public media to keep the public well-informed of the water

supply status and drought conditions that lead to requests for voluntary or mandatory water use restrictions. Moreover, it has responsibility for requesting assistance from governmental agencies and other organizations such as international organizations and non-governmental organizations to coordinate in mitigation of impacts.

The drought committee is divided into subcommittees referred to as a monitoring committee, an impact assessment committee, and mitigation and response committee, where each committee has its own taskforce. The monitoring and impact assessment committees are responsible for reporting the occurrence and severity of drought and its impacts on sectors, and recommending mitigation and response actions to the drought committee. If potential impacts are recognized by the impact assessment committee, then the mitigation and response committee is assigned to implement measures to lessen drought impacts on sectors. The activities related to mitigation and response should be implemented by a close cooperation among localities, ministries, organizations, universities and research institutes. The members of a drought committee should include appropriate representatives of various governmental agencies, key stakeholders, relevant research institutes and universities where appropriate specialized experts are available. After each drought, achievements and lessons learnt need to be collected in a report to be delivered to all participants and related organizations to ensure that follow-up activities will be closely cooperative and efficient.

The monitoring committee is a group of technical staffs belonging to relevant hydro-meteorological services being responsible for monitoring and providing outlook for short- and long-term information on water availability and climate such as precipitation, air temperature, evaporation, soil moisture, stream flow, groundwater head, and reservoir levels. Such elements might be transformed to drought indices to visualize drought occurrence, reflect impacts on agriculture, households, industry, transportation, recreation and tourism, and they need necessarily to be included in the evaluation reports of current water availability and outlook. The reports should be prepared and disseminated to the drought committee, relevant governmental agencies and public media. The monitoring committee should work closely with public media to keep the public well informed about changing conditions.

The impact assessment committee is composed of technical work groups that are assisted by specialists from relevant research institutes, universities and ministries. They are responsible for identifying and assessing significant drought impacts on the environmental, economic and social sectors, and make appropriate and reasonable recommendations in terms of mitigation measures to the drought committee. The analyses, findings, and data dissemination of current and prior drought events must be reported to the drought committee.

The mitigation and response committee is built up by local authorities and stakeholders with assistance from specialists, governmental agencies and organizations. The committee has the responsibility for implementing mitigation and response actions

to reduce drought impacts, and for estimating the costs of these actions and reporting to the drought committee. The funding for these actions should be sought through various governmental and non-governmental agencies. The mitigation and response committee should work in collaboration with the monitoring and impact assessment committees to stay well informed about drought conditions, and prepare appropriate response actions in due time. The members of the committee should have sufficient knowledge and experience to understand drought mitigation techniques, risk of sectors, and decision-making processes at any levels of government. The number of appropriate actions depends on drought severity, affected sectors and the exposures of vulnerability of sectors to drought, which are identified and included in the report of the impact assessment committee. The obvious roles of the local authorities are to implement mitigation and response actions at field level following the guidelines of the drought committee. They take the main responsibility to identify activities and priority areas to implement appropriate actions. They monitor and participate in evaluation of the efficiency of the mitigation and response implementation process. Finally, they make recommendations on solutions and provide feed-back information to the drought committee and relevant political leaders.

4.4.4 Implementation of solutions

Besides the response policy mentioned, other policies and solutions in terms of water resources need to be taken into account in order to achieve a good drought mitigation process and a sustainable development. This section is based on the water law adopted by the National Socialist Republic Assembly of Vietnam in May 1998, the decree 91/2002/ND-CP in terms of duties and rights for implementation of solutions in relation to water resources management and others references related to the topic including *Hieu[2002], Thanh[2002], Hoc[2002]* and *NAP[2002]*.

Drought mitigation measures must adopt an integrated approach based on a comprehensive survey and evaluation of water resources management, use of the most suitable drought-resistant species with minimum water demand, and a better regulation of water distribution. The structural measures play a very important role in water allocation and water supply due to the complex topography, temporal and spatial rainfall distribution, and varying water demand. Besides the structural measures of water resources development and management for dealing with water deficits, non-structural measures are essential and helpful to ensure strong effectiveness of water resources development and management and economic development plans. It is essential to strengthen research on science and technology and technology transfer activities needed for development of society. The research should be more demand-oriented with respect to both technique and management in relation to sustainable water resources development in general, and for drought preparedness and mitigation aspects in particular. Research results should be shared among research institutes and

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universities to enhance close collaboration and improve research methodologies. Moreover, an effective communication mechanism is essential in drought mitigation and response processes related to disseminating and sharing information, knowledge and experiences within sectors, among sectors, among regions, and among countries and international organizations.

As any other action program, a drought mitigation program needs a joint approach to mitigate the effects of droughts, reduce poverty alleviation and enhance sustainable development. This should be considered very carefully in the formulation and implementation of the process. Partnership arrangements for the drought task force are essential, being one of the effective tools for resource mobilization and strengthened cooperation among agencies and organizations in a combined effort on drought mitigation and response implementation, environmental protection and sustainable development. By collaborating, the partners aim at maximising effectiveness and efficiency in mobilization and use of all resources available. Training the management and technical staffs should be prioritized, especially at the local level, to ensure that adequate knowledge and skills are efficiently involved in all activities related to drought mitigation and response processes.

5. Summary and conclusions

Drought occurrences are regular in Vietnam and have been of high concern for the government in recent years. It may occur at any time around the rainy season due to rainfall deficit over an extended period, although it mostly occurs at the end of the dry season, especially over the central highlands. Droughts cause potential damage to both livelihood and economic development like other natural hazards such as flooding, typhoons but are very difficult to recognize due to the creeping development characteristic. Understanding the influence of SST on precipitation over the VCH through large scale-circulation plays a significant role in development of forecast models and in operation of monitoring systems in terms of early drought warning.

The investigation of the relationships between SST in the Pacific and Indian oceans and the intraseasonal variability of precipitation over the Vietnamese central highlands using singular value decomposition (SVD) showed that the relationships vary significantly through the rainy season.

The rainfall variations over the VCH are most sensitive to SST changes in April, October and November. The SST changes can significantly influence the monsoon onset and withdrawal during the early and late rainy seasons, respectively. In June to September, the analyses reveal that rainfall variations over the VCH are weakly correlated with SST anomalies in both basins. The lag-time relationships between precipitation and SST revealed that the Pacific SST is well correlated with the rainfall one to three months in advance throughout the rainy season, except in August. For the Indian Ocean, significant lag-time relationships (one and two months) were found

between the Indian Ocean SST and the VCH precipitation in October and November. Especially in the months of October and November, high lag-time correlations between precipitation over the VCH and SST patterns in both oceans were observed. Those results provide a strong basis for a predictive scheme. Throughout the rainy season the SST in the Pacific Ocean has a more significant influence on the precipitation over the VCH than that in its counterpart, the Indian Ocean.

Canonical correlation analysis (CCA) was employed to develop linear models for forecasting monthly precipitation over the VCH based on Pacific and Indian Ocean SST throughout the rainy season. A diagnose was made by means of CCA to find the temporal and spatial evolution in the predictor field that gives the best forecast skill to the predictand field, the so-called canonical predictor pattern (g-map). EOF was applied to both SST and the precipitation field to develop linear models. The model forecast skills vary significantly, temporally and spatially, because the precipitation over the VCH is influenced by the local climate as well as the large-scale circulation patterns governing the prevailing winds during the year. The local climatic patterns are mainly formed by the south Asian monsoon in combination with the topographical conditions in the region.

It is found that February SST in the equatorial central to eastern Pacific Ocean, representative of the El Niño-Southern Oscillation phenomenon, is a key factor for rainfall forecast in the early rainy season, and that September SST in the equatorial eastern Indian Ocean is a good predictor for the rainfall at the end of the rainy season. During the main rainy season, heavy rainfall over the VCH is primarily caused by cyclones, typhoons and other disturbances associated with complex atmospheric large-scale circulations, so in this period few significant results could be obtained from the models based on only SST.

Therefore artificial neural networks (ANN) were employed to estimate monthly rainfall over the region at the early rainy season to further improve the persistent results obtained in the previous studies. The quality of the rainfall forecasts varies spatially and improves southward reflecting that the southern parts of the VCH are more clearly influenced by large-scale circulations than the northern parts. A significant improvement of the forecasts is obtained when the input to the models contains both SST and local climatic variables. The poorest results are obtained from the models at sites where no meteorological variables are available and the rainfall regime is mainly characterized by the local climate. Moreover, ANN was also used to forecast discharge time series at three sites in three different catchments of the VCH based on SST and local variables available such as humidity, wind speed, air temperature and discharge etc. Very good results obtained from such ANN models imply that ANN has a potential to forecast discharge and rainfall over the VCH, which could contribute significantly to early drought warning in the region.

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A legal organisational framework, a drought committee, is found necessary to supervise and coordinate development of drought planning corresponding to the multidisciplinary nature of drought and its impacts. In general, the drought committee comprises a monitoring committee, an assessment committee, and a mitigation and response committee. The members of the drought committee should include appropriate representatives of various governmental agencies, key stakeholders, relevant research institutes and universities where appropriate specialized experts are available. The activities on mitigation and response are implemented in a close cooperation between local entities, ministries, organizations, universities and institutions.

In terms of policy, drought and response measures are divided into three scenarios corresponding to pre-alert, alert and emergency situations. Only certain measures are considered feasible and potentially effective in a certain drought situation. The possible actions should be implemented through stakeholder seeking, information dissemination on encouragement or enforcement of water savings, restriction of certain uses, and focus on water resources conservation and environment protection in pre-alert and alert situations. A number of legislative measures should be adopted for the emergency cases of extreme droughts including restrictions of water use and increased pricing of water together with possible palliative measures such as aid programs, healthcares etc. Moreover, to deal efficiently with droughts mitigation and response measures need to be in closely combined with science and technology policy, training and education, and public communication and information, from the governmental to the local level, sharing information between regions and countries and complying with the concept of sustainable development.

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Appendix

Drought: Early warning, mitigation and response in the central highlands - Vietnam

DTU

Technical Report

by

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Executive summary

Drought is considered a worldwide phenomenon affecting broad regions and causing significant damages, both in terms of human lives and economic losses. Droughts cannot be prevented but much can be done to reduce impacts on the environmental, social and economic sectors through preparedness and mitigation. Droughts can be defined in several ways; here meteorological droughts and hydrological droughts are defined and expressed by a standardized precipitation index and a surface water supply index, respectively. It seems that both indices are potential drought indicators over the Vietnamese central highlands, as they can be used for monitoring drought occurrence as criteria to assess drought severity, and for implementation of mitigation and response actions. One of the most important components in drought mitigation is early warning; establishment of a drought monitoring system is essential in playing a very important role for early drought warning. A conceptual drought monitoring system in the central highlands is proposed based on climate variables that provide valuable information of droughts in advance and explain the response of droughts to climate variability. Early drought warning would provide valuable information of the signal and trend of drought occurrence, severity and duration to decision-makers and stakeholders to help them prepare and take appropriate actions in due time to reduce impacts. Moreover, drought mitigation and response policy and a drought organizational structure are suggested including implementation of a drought task force. Besides that, an implementation solution in terms of water resources management, science and technology promotion, training and education, communication and information enhancement, and especially partnership and arrangement, is identified to reinforce the drought task force dealing with impacts on affected sectors and to enhance sustainable development.

I. Introduction

Drought is a natural phenomenon, it occurs in virtually all climate regimes with potential impacts on the environmental, economic and social sectors [*Wilhite 2001a*]. Drought cannot be prevented but much can be done to reduce impacts through preparedness and mitigation [*Wilhite et al. 2000*]. Due to its creeping evolution it takes a significant amount of time for the impacts of droughts to emerge [*Tannehill 1947*]. Taking advantage of this feature, an effective mitigation of the most drought impacts maybe possible, more than compared to other natural hazards such as floods and hurricanes. The primary purpose of a drought task force is to address the needs for coordination and implementation of measures related to preparedness and mitigation of the adverse impacts of droughts. The measures should be long-range proactive, strategic and tactical, to prepare optimally for drought mitigation and respond adequately.

Water quality, quantity and availability affect the well-being of all residents in the Vietnamese central highlands (VCH). Rainfall is plentiful but it is not well-distributed temporally, as it is concentrated in a rainy season with about 80% of the total annual amount. When water supply is scarce to meet the demand, people must compete for the available water supply. Initially, only a few water users are directly affected, e.g., crops and livestock, but in the case of a severe and prolonged drought every water user is directly affected, and even sectors that do not use water may be affected due to the huge water shortage. A drought task force should identify issues related to drought impacts and the vulnerability of sectors exposed to droughts, and recommend and prepare implementation of measures to mitigate effectively water shortage in any drought situations.

Early drought warning is one of major components that lead to implementation of mitigation measures, timely and effectively. A comprehensive early drought warning system has been discussed in the United States [*Wilhite and Wood 1994; Wilhite 1997a*], and a wide range of data and information are now readily accessible to users via the internet at the U.S national Drought Mitigation Centre, which makes the development of a drought monitoring system more executable. A good monitoring system would allow the managers to identify the status of water supply capacity and water availability, and estimate trends of water components such as water level in reservoirs and in rivers, discharge and other elements. Moreover, long-term forecasts should be provided to help decision-makers and managers to get a comprehensive picture of present and future drought conditions. Appropriate measures can be prepared for implementation according to drought scenarios to lessen impacts on humans and environment.

Drought mitigation and response measures are the actions taken during drought occurrence by appropriate governmental agencies, organizations and citizens to lessen some of the impacts on the environmental, economic and social sectors. A number of measures can be applied effectively to a certain drought condition in a certain region,

depending on the drought severity and the vulnerability of the region to droughts [*Blaikie et al. 1994*]. The actions are taken under provision of the Water Law enacted by the National Socialist Republic Assembly of Vietnam in May 1998, which brings a strong legal power to carry out water resources management to ensure that the quality and quantity of water resources are maintained at the highest level to support present and future beneficial uses.

II. Early drought warning

Before the early warning system is activated, a practical drought index should be provided. Then certain thresholds, also called trigger points, need to be determined so that certain activities are adopted when the drought index exceeds a threshold. Since no single index is adequate to evaluate meteorological, agricultural, or hydrological droughts, a variety of indexes should be used.

II.1 Drought indices

A drought index is typically a single number that assimilates individual or a combination of different data into a comprehensible picture for drought assessment. There are several indices that measure certain drought types for a given period based on a single type or a combination of historical data, e.g., the Palmer Drought Severity Index, the Crop Moisture Index, the Standardized Precipitation Index and the Surface Water Supply Index. Some indices are better than others for some particular uses [*Hayes 1998*], and they require different types of data to generate. Here, we use only the Standardized Precipitation Index (SPI) to measure meteorological droughts and the Surface Water Supply Index (SWSI) for hydrological droughts in three catchments over the VCH due to the limitation of available data types.

II.1.1 Standardized Precipitation Index

The SPI is an index based on a precipitation record for a given location and a given period (months or years). *McKee et al. [1993]* developed the SPI to quantify the precipitation deficit for multiple time scales, hereby reflecting short-term and long-term impacts of drought on water resources availability in terms of, e.g., soil moisture, groundwater, stream flow, and reservoir storage. The SPI has found widespread application, see, e.g., *Heim [2000], Rossi and Cancelliere [2002]*. It is able to take into account the different time scales at which drought phenomena occur, and it is used to compare drought conditions amongst different time periods and regions with different climate conditions due to its standardization [*Bonaccorso et al. 2003*]. *McKee et al. [1993]* use the classification system such that both wet and dry climate can be presented by means of the SPI. The index is calculated based on the probability of a given precipitation amount, and standardized such that zero denotes the median precipitation amount. A positive index indicates wet conditions and vice versa. The more severe wet or dry conditions become, the more positive or negative the index appears. In the other

words, positive and negative SPI values show above and below mean precipitation amounts, respectively. In addition, the wetness and dryness can be monitored using the SPI as a criterion for any time scale. Precipitation deficit occurs only if the SPI is negative and vice versa. The accumulated magnitude of deficits during a dry period can be referred to as drought magnitude. Table 1 shows drought intensities based on SPI values for arbitrary time scales. For the mathematic expression of SPI and how SPI is developed, the readers are directed to *McKee et al. [1993]*.

Table 1 Meteorological drought classification based on SPI values

SPI Values	
+2.0 and above	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-0.99 to 0.99	near normal
-1.0 to -1.49	moderately drought
-1.5 to -1.99	severely drought
-2.0 and below	extremely drought

Here, the SPI has been calculated using average monthly precipitation at selected stations over each catchment in the VCH. The SPI time series spanning January 1980 to December 2000 in the three catchments Sesan, Srepok and Ba are presented in Fig. 1.

As shown in Fig. 1, SPI values vary significantly, temporally and spatially within three catchments in the VCH reflecting the fact that rainfall over the VCH is not only influenced by large-scale atmospheric circulation but also depends on local weather regimes. However, the SPI values illustrate well dry and wet condition in these three catchments, especially during El Niño episodes. The SPI values correspond well to statistical records of drought occurrence over the period 1980 to 2000 over the VCH as obtained from the national Hydro-meteorology centre and local authorities. Two severe drought events affected summer crops in 1993 and 1998 and moderate droughts affected winter-spring crops in 1983, 1993, 1998 as well as summer crops in 1982, 1985 and 1988. Table 2 presents the SPI values during some severe drought years in the VCH, 1983, 1993 and 1998. Most SPI values are negative during these years. A large-scale drought occurred over the VCH from early spring to end of summer in 1998 corresponding to high negative SPI values, and it had severe impacts on the social-economic sector in the region. On this background the SPI is found to be a good indicator to illustrate the occurrence, intensity and magnitude of meteorological droughts based on precipitation records. Therefore, it can be used for drought monitoring and assessment in the three river catchments of the VCH.
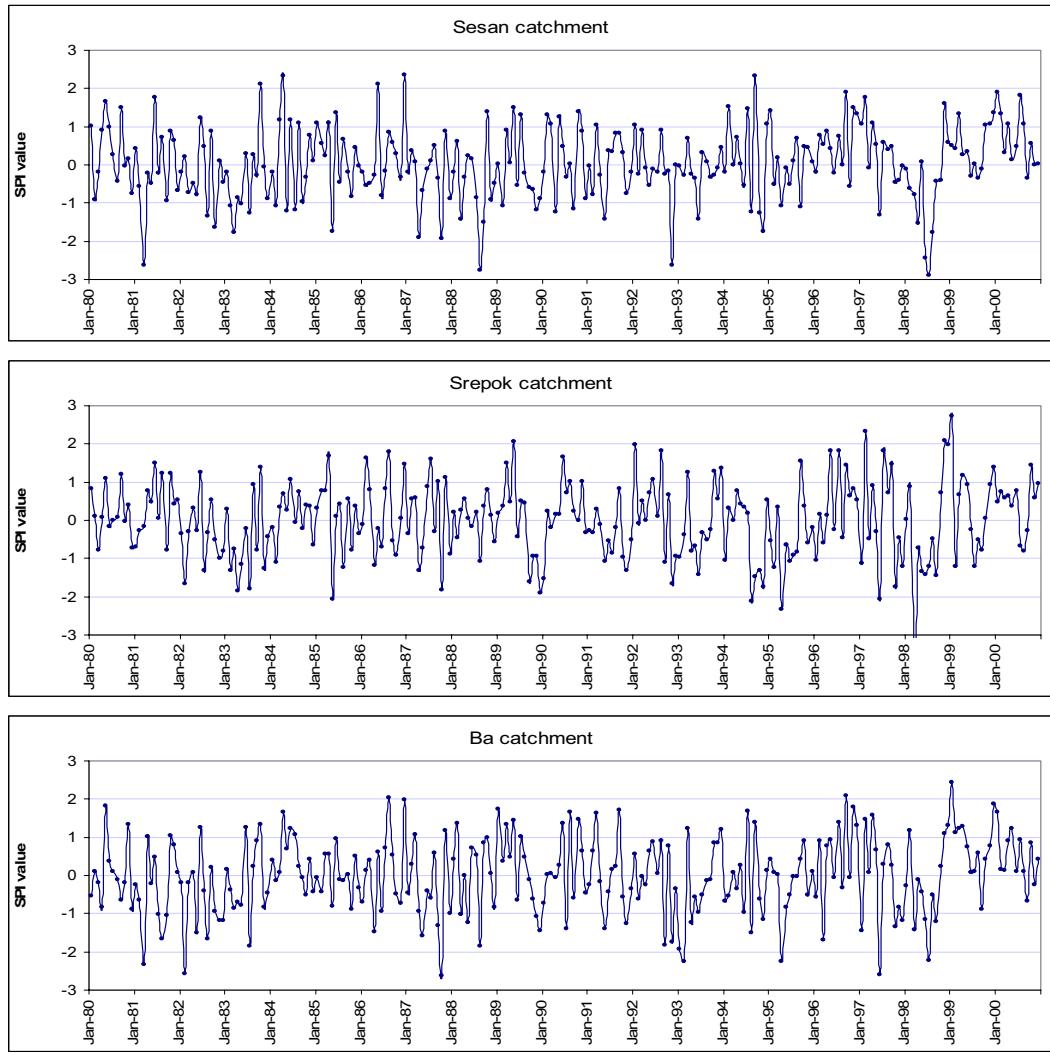
Fig. 1 Time series of monthly SPI values in three catchments over the VCH for the period January 1980 to December 2000.

Table 2 SPI values during severe drought years in the VCH

Month/year	Sesan			Srepok			Ba		
	1983	1993	1998	1983	1993	1998	1983	1993	1998
January	-0.2	0.0	-0.1	0.3	-1.0	0.0	0.2	-1.9	-0.3
February	-1.1	-0.3	-0.6	-1.3	-0.4	0.9	-0.4	-2.3	1.2
March	-1.8	0.7	-0.8	-0.8	1.3	-3.7	-0.9	1.2	-1.4
April	-0.9	-0.3	-1.5	-1.9	-0.8	-0.7	-0.7	-1.2	-0.1
May	-1.0	-0.4	0.1	-1.2	-0.7	-1.4	-0.8	-0.6	-0.4
June	0.3	-1.4	-2.5	-0.2	-1.4	-1.4	1.3	-1.0	-1.2
July	-1.3	0.3	-2.9	-1.8	-0.3	-1.2	-1.9	-0.5	-2.2
August	0.3	0.1	-1.8	0.9	-0.5	-0.5	0.3	-0.1	-0.5
September	-0.3	-0.3	-0.4	-0.8	-0.2	-1.4	0.9	-0.1	-1.2
October	2.1	-0.3	-0.4	1.4	1.3	0.7	1.3	0.9	0.2
November	-0.1	-0.1	1.6	-1.3	0.6	2.1	-0.8	0.9	1.1
December	-0.9	0.5	0.6	-0.4	1.4	2.0	-0.5	1.2	1.3

II.1.2 Surface Water Supply Index

The surface water supply index (SWSI) is based on incorporation of both hydrological and climatological features into a single index for application to river basins. It was originally developed and applied in Colorado, USA [*Shafer and Dezman 1982*] and is adopted by several states in the United States. The SWSI originally integrates reservoir storage, streamflow and two precipitation types into a single index. Calculations are performed with a monthly time step in which weight coefficients are assigned to each water balance component corresponding to its typical contribution to surface water within each catchment. The SWSI is used to identify hydrological drought severity based on the classification presented in Table 3.

Table 3 Hydrological drought classification based on SWSI values

SWSI Values	
above 4.0	extremely wet
3.0 to 4.0	very wet
2.0 to 2.99	moderately wet
1.0 to 1.99	Slight wet
-0.99 to +0.99	near normal
-1.0 to -1.99	slight drought
-2.0 to -2.99	moderately drought
-3.0 to -4.0	severely drought
below -4.0	extremely drought

In the VCH there is no snow contribution to the water balance, and the SWSI is generally expressed as follow:

$$SWSI = \frac{aP_{rain} + bP_{strm} + cP_{resv} - 50}{12}$$

where a, b and c are weights for rain, streamflow and reservoir storage, respectively, and the sum of the weight coefficients is equal to one. P_i is the probability (%) of non-exceedence for each of these water balance components. Subtracting 50 and dividing by 12 are the normalization procedure designed to obtain SWSI values ranging in interval [-4.2 +4.2]. The SWSI is relatively easy to calculate, and it gives a representative measure of water availability in a river catchment or a selected region. However, it is likely that it could not be successfully used for large regions with significant spatial hydrological variability because the weights may differ substantially from one part of the region to another [*Doesken et al. 1991*]. The hydrometeorological regime, however, does not vary much within each of the three catchments Sesan, Srepok and Ba in the VCH, why the index is assumed to be a good indicator for hydrological drought. The weight coefficient of each water balance component is estimated according to actual experience from water resources planning and management in the region. Due to limited documentation of reservoir storage and operation over the VCH, rainfall and streamflow contribute dominantly to the water balance. The weight coefficients are applied to all catchments over the VCH and presented in Table 4. Time series of the SWSI spanning

January 1980 to December 2000 in three catchments are presented in Fig. 2. In general, the SWSI values present well the hydrology variability in the studied catchments over the VCH. During most dry periods the SWSI values are negative, and particularly high negative SWSI values coincide with El Niño events in 1982/83 and 1997/98.

Table 4 Weight coefficients of water balance components in the VCH

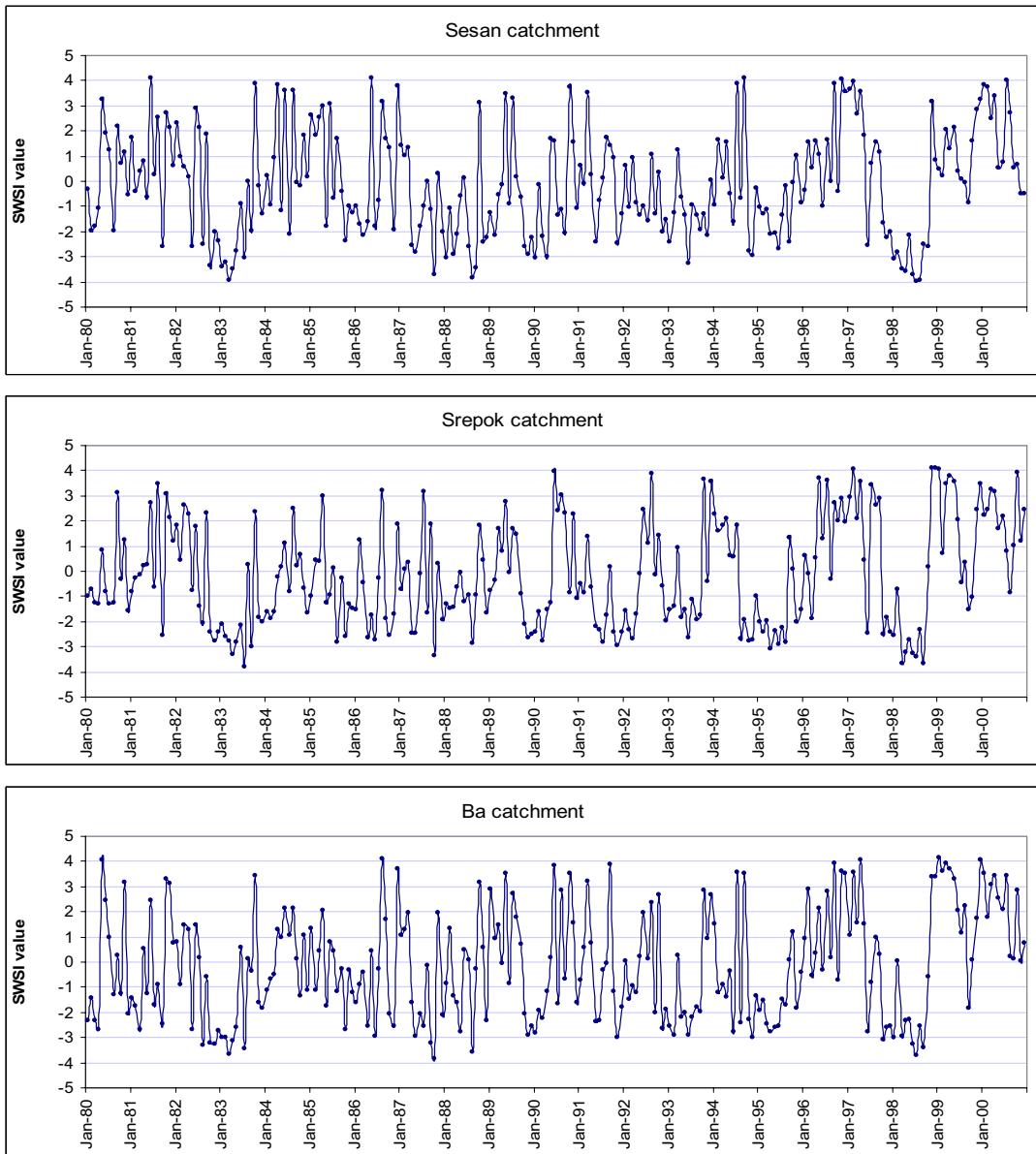| Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
a	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.3	0.2
b	0.8	0.8	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.7	0.8
c	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 2 Time series of monthly SWSI in three catchments over the VCH for the period January 1980 to December 2000.

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Table 5 shows the SWSI values in three selected drought years in the VCH, and it is seen that the most severe drought events correspond to the highest negative SWSI values during the drought periods. In Table 5 negative SWSI values occur from January to September corresponding to drought events in all selected years, and particularly high negative values (around -3.0) are obtained during severe droughts as experienced for winter-spring crops in 1983, 1998 and for summer crops in 1998. Moreover, the SWSI values also illustrate well the flood events in the studied period as expressed by high positive values (above 3.0) in November and December 1998 associated with a La Niña event. Thus, the SWSI can be used as a potential index to monitor and assess hydrological droughts over the VCH and thereby help effectively decision-makers in water resources planning and management.

Table 5 SWSI values during severe drought years in the VCH

Month/year	Sesan			Srepok			Ba		
	1983	1993	1998	1983	1993	1998	1983	1993	1998
January	-3.4	-2.4	-3.1	-2.1	-1.5	-2.5	-3.0	-2.6	-3.0
February	-3.2	-1.3	-2.8	-2.6	-1.4	-0.7	-3.0	-2.9	0.0
March	-3.9	1.2	-3.5	-2.8	0.9	-3.7	-3.7	0.3	-3.0
April	-3.5	-0.6	-3.6	-3.3	-1.8	-3.2	-3.1	-2.2	-2.3
May	-2.8	-1.3	-2.2	-2.8	-1.5	-2.7	-2.6	-2.0	-2.3
June	-0.9	-3.3	-3.7	-2.1	-2.6	-3.3	0.6	-2.9	-3.2
July	-3.0	-0.9	-4.0	-3.8	-1.1	-3.4	-3.4	-2.2	-3.7
August	0.0	-1.3	-3.9	0.3	-1.9	-2.3	0.1	-1.8	-2.5
September	-1.9	-1.9	-2.5	-3.0	-1.7	-3.7	-0.4	-1.9	-3.4
October	3.9	-1.3	-2.6	2.4	3.7	0.2	3.4	2.9	-0.6
November	-0.2	-2.2	3.2	-1.8	-0.4	4.1	-1.6	0.9	3.4
December	-1.3	0.0	0.8	-2.0	3.6	4.1	-1.8	2.7	3.4

II.2 Drought monitoring

A drought monitoring system should be established to provide timely information on the formation, development, persistence, trend, and end of a drought to those responsible for responding to the drought. It should be able to capturing, analyzing, and transferring drought information timely and setting up criteria to confirm drought-affected zones, monitor the current status and estimate the trend of water availability to enforce early drought warning.

In order to monitor the occurrence and development of droughts efficiently and provide information on strength and range of the drought, a robust system of indicators should be determined that is able to identify and diagnose anomalies in water availability. Multiple indicators should be used to illustrate drought extension and severity, which would enhance the effectiveness of drought mitigation and the response process, since no single indicator can encompass the complexity of drought development [*Hisdal and Tallaksen 2000*]. A comprehensive study of suitable drought indices would lead to a good drought indicator system that takes into consideration the

availability of new information and progress of the drought condition over the region. Values that significantly differ from normal values of precipitation or a combination of precipitation and discharge values, as given by the standardized precipitation index or the surface water supply index, can be used as key drought indicators in the VCH. Moreover, evapotranspiration (ET) and soil moisture (SM) need to be considered to supplement in drought occurrence identification. The combination of drought indicators can provide decision-makers with sufficient information to understand the drought phenomenon and estimate its impacts on the environmental, economic and social sectors. When the development of a meteorological drought is being discussed, as presented by SPI values, the water managers should check for the trend of discharge, or SWSI values, and combine with evapotranspiration and soil moisture information in order to identify whether there is a significant risk of water shortage or not.

A drought monitoring system could be composed of a network with selected key gauging stations available in the region. The drought conditions may be viewed on a digital map on a website and should be colour-coded in gradient colour from blue presenting no drought occurrence to red indicating extreme drought conditions. The colour would be changed according to indicators dropping below certain percentile marks, e.g., when an SPI value is going below -2.0 the colour should change to red. By regularly accessing monitoring system, water resources managers would be able to see the status and trend of drought development, and then appropriate mitigation and response measures can be taken corresponding to the drought severity situation. Moreover, an additional tool should be included on the digital map to help users view detailed information at a particular site such as summary indicator statistics and graphic plots. As defined in *Demuth and Stahl [2001]* and *Wilhite et al. [2005]*, the drought monitoring system is generally responsible for:

- Identifying drought management areas by subdividing the region into subregions sharing similar hydrological and climatological characteristics in which it is suitable to implement mitigation and response actions.

- Monitoring drought occurrence and development by clearly determining the drought characteristics at various time scales, consecutively monitoring the drought evolution and identifying the trend of other meteorological and hydrological elements to enforce early drought warning.

- Displaying drought distributions over the region, and determining as soon as possible the geographical positions where droughts are occurring.

- Comparing and ranking the severity, duration, and extent of drought events to improve understanding about drought characteristics and help the water managers and decision-makers in preparation and implementation of mitigation and response measures.

- Inventorying and prioritizing data quantity and quality from the current observation network to improve indictors that are able to reflect significant drought impacts on different sectors, and to deliver information effectively to the users.
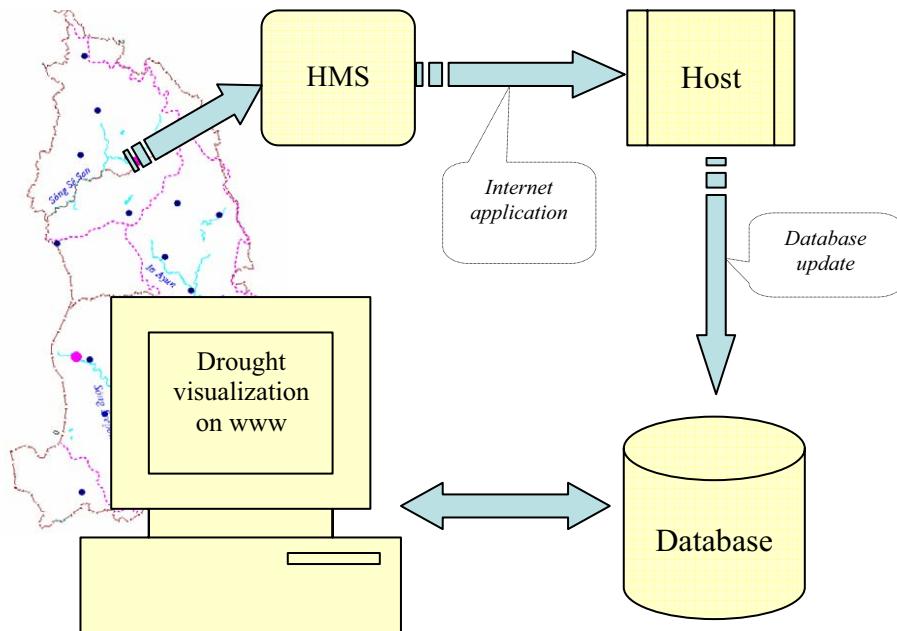

Fig. 3 Proposal for drought monitoring system design (source *Demuth and Stahl 2001*)

The conceptual design of the monitoring system is presented in Fig. 3. The system obtains the data from the relevant Hydro-meteorological service (HMS) by internet technology such as email and telecommunication network. The host organisation is responsible for receiving data from the HMS and updating to the database. Models are used to visualize drought indicators on public websites and provide statistical records of drought features to the database. From the user-interface of the website, the users can click on any station to view details of drought information and other hydrological and meteorological characteristics. The procedure to visualize droughts is briefly illustrated in Fig. 4. The database is responsible for supplying data to the models, e.g., precipitation for simulating SPI values, and discharge and precipitation to simulate SWSI values, and other data such as air temperature, wind speed and radiation to estimate soil moisture and evapotranspiration. The combination of indicators would present a comprehensive picture of drought occurrence and severity, which plays a significant role in decision-making in terms of drought mitigation and response over the region.
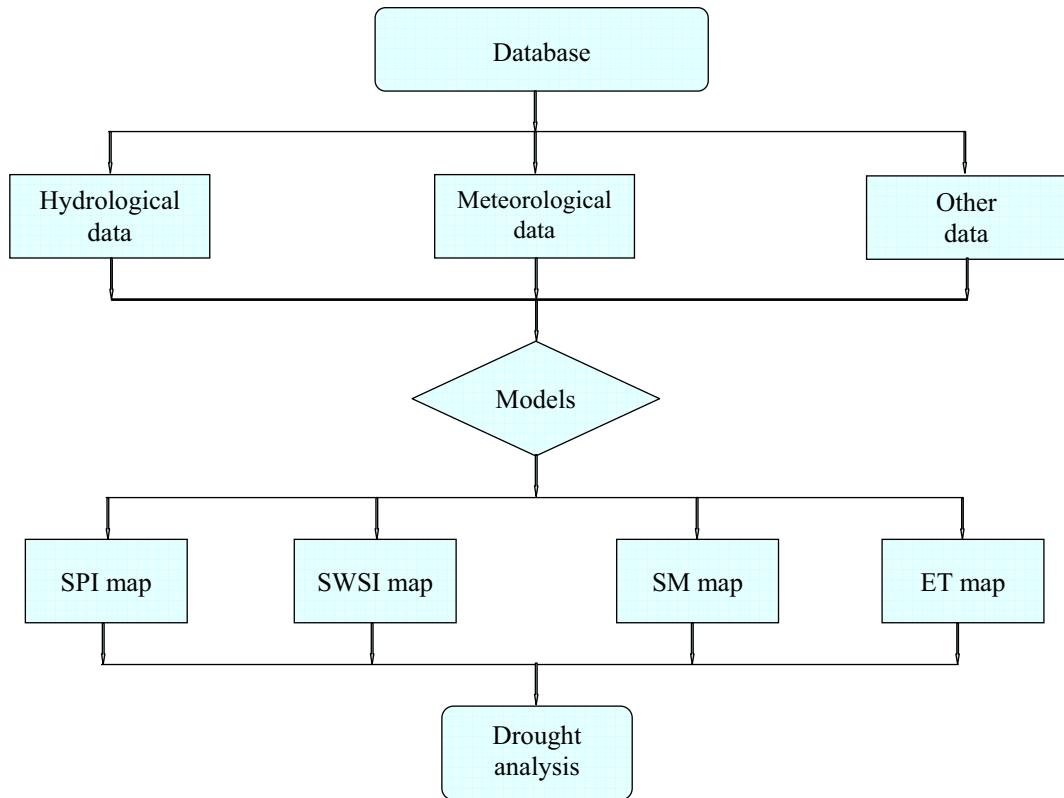
Fig. 4 Proposal for drought visualization procedures (*Demuth and Stahl 2001*)

The proposed conceptual monitoring system clearly shows that it would be possible to develop a comprehensive operational drought monitoring system in the VCH as well in the whole country. However, to reach such target we need to address a number of different issues and overcome various technical and non-technical barriers. The data obtained from a network of gauging stations should be good long-term historic records, sufficiently dense to be fully representative of drought conditions over the region. The monitoring system should be closely collaborating with HMS agencies at relevant levels. The primary processing of the data at the HMS and the subsequent submission to the drought monitoring system should be automated; the observed data needs to be presented by some telemetry forms so that they are easily transmitted to relevant usage purposes. Moreover, infrastructures as well as the high technologies applied need to be well-set up by well-qualified staffs with sufficient ability to control the system.

II.3 Forecasting

II.3.1 Data

The region selected for assessing the forecast potential in the VCH consists of the three catchments Sesan, Srepok and Ba. Datasets used as input to Artificial Neural Networks (ANN) models are average monthly precipitation over each catchment and monthly discharge at a site in each catchment, Kontum (Sesan catchment), Bandon

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(Srepok catchment) and Cungson (Ba cathcment). The data values span the period January 1980 to December 2000 in which the data sets are divided into three subsets, 13 years for calibration, next 3 years for checking and the last 5 years for validation.

Additional inputs are sea surface temperatures (SST) in equatorial eastern Pacific ranging from 5°N-5°S; 150°W-90°W (referred to as the NIÑO3 region, where a large variation in term of sea surface temperature can be observed in the warm ENSO phase), which is obtained from the Comprehensive Ocean Atmosphere Data Set (COADS) [*Reynolds et al. 2002*] and extracted from the data library of the International Research Institute for Climate and Society - IRI. The data, available at a 2°x2^{o} lat-long grid point resolution, were transformed into a single time series by simple averaging. Moreover, meteorological data such as air temperature, humidity, wind speed etc. were also used as model input. These data were obtained by simple averaging of all stations available over each catchment in the VCH.

All time series were standardized, prior of use, by extracting the long-term mean value and dividing by the standard deviation. After this standardization, as suggested by *Dawson and Wilby [2001]*, all data series were transformed to the interval [-0.9, 0.9]. Validated results of the models are converted back to original precipitation and discharge values.

II.3.2 Method

An artificial neural network (ANN) is conceptually composed of simple elements working in parallel, which are inspired by the biological nervous system. Mathematically, ANN is a theorized mind model in which the network function is identified by interconnecting elements in the system. Thus, a neural network can mimic non-linear complex relationship by adjusting the weights that link the interconnected elements in the network. The ANN is considered as a universal estimator based on a flexible mathematical structure that can imitate arbitrary non-linear complex relationships between input and output data in any systems [*Hsu et al.1995*]. The optimal design of an ANN is normally identified by trial and error tests. Here, the best accuracy was achieved when using a multi-layer feed-forward neural network. The ANN is constructed of three layers in terms of input-hidden-output layers. The output layer has one neuron, and the input layer contains as many neurons as the number of input variables. The number of the neurons in the hidden layer was chosen through test runs with a small number to begin with and gradually increasing the network size. A hyperbolic tangent sigmoid transfer function is used in the neurons of the hidden layer and in the output layer, and the ANN was developed using MATLAB.

The hyperbolic tangent sigmoid transfer function is expressed as follow:

$$a = \frac{e^{n} - e^{-n}}{e^{n} + e^{-n}}$$

where n is input and a is output.

During the training process, the ANN weights and bias factors are estimated. The scaled conjugate algorithm that is used in this work ensures super linear convergence by using a step size scaling mechanism so that it avoids time consuming line-search in each learning iteration [*Moller 1993*].

The important issue in development of an ANN is generalization. If too many layers and neurons are used, the network has too many free parameters and may overfit the data. In contrast, if too few layers and neurons are used, the network might not be able to fully detect the signal and the variance in a complex data set. Therefore, an optimal ANN need to be identified by considering the optimal number of layers and neurons in each layer and a suitable transfer function and training technique. The scaled conjugate algorithm is used to train network because it is a sufficiently accurate and robust technique to train the network [*Moller 1993*]. Time-consuming overfitting can be avoided such that a satisfactory generalization would be archived by adopting a stopping rule corresponding to an error between one iteration and the next as small as 0.001 or after 300 epochs.

II.3.3 Results

The results of rainfall and discharge forecast obtained from ANN models are presented in details in Table 6 and Figs. 5 and 6. In general, the models are potentially able to forecast rainfall and discharge over the VCH, the correlation coefficient ranges in the interval of 0.75 to 0.88. The resulting forecast for discharge seem better than for rainfall forecast expressed by the higher correlation coefficient in all catchments. The models cannot catch the peaks of both rainfall and discharge. This might be because the inputs to the models do not contain enough information about the peaks and the fact that most heavy rainfall events over the VCH are caused by storms, typhoons that in a complex way are influenced by large-scale circulation.

Table 6 Forecast results obtained from ANN models for three catchments over the VCH.

Catchment	Predictand	Input to network	Network Structure	Cor.coeff	RMSE
Srepok	Precipitation	SST_2, H_1, $T_{1-max,,min,mean}$	5-7-1	0.82	67.3
	Discharge	SST_2, H_1, $T_{1-max,min,mean}$, n, Q_1	7-10-1	0.82	162.6
Sesan	Precipitation	SST_2, H_1, $T_{1-max,min,mean}$	5-7-1	0.77	85.9
	Discharge	SST_2, H_1, $T_{1-max,min,mean}$, Q_1	6-7-1	0.78	51.3
Ba	Precipitation	SST_2, H_1, $T_{1-max,min,mean}$	5-7-1	0.75	73.4
	Discharge	SST_2, H_1, $T_{1-max,min,mean}$, Q_1	6-7-1	0.88	210

The inputs to the ANN models are: sea surface temperature (SST), humidity (H), air temperature (T), sunshine hours per month (n) and discharge (Q). The subscript shows the lag time prior to the forecast. The network structure information indicates the number of neurons in, respectively, the input-hidden-output layers, and RMSE stands for the root mean squared error.

Fig. 5 shows the results of rainfall forecast for three catchments over the VCH. The left panels present the results for the training period and the right panels the results

for the validation period. As apparent from the scattered points (left panels), it is clear that the models tend to underestimate extreme values, while it presents well the below-normal values. This implies that drought conditions can be well-predicted in advance. The right panels show the time series of observed (solid line) and estimated (dash line) rainfall values. The ANN inputs include two-month lag SST in El Niño3 area and one-month lag humidity and air temperature. Good results are obtained by the AAN models as expressed by the correlation coefficients between observed and estimated values obtained for Srepok (0.82), Sesan (0.77) and Ba (0.75).
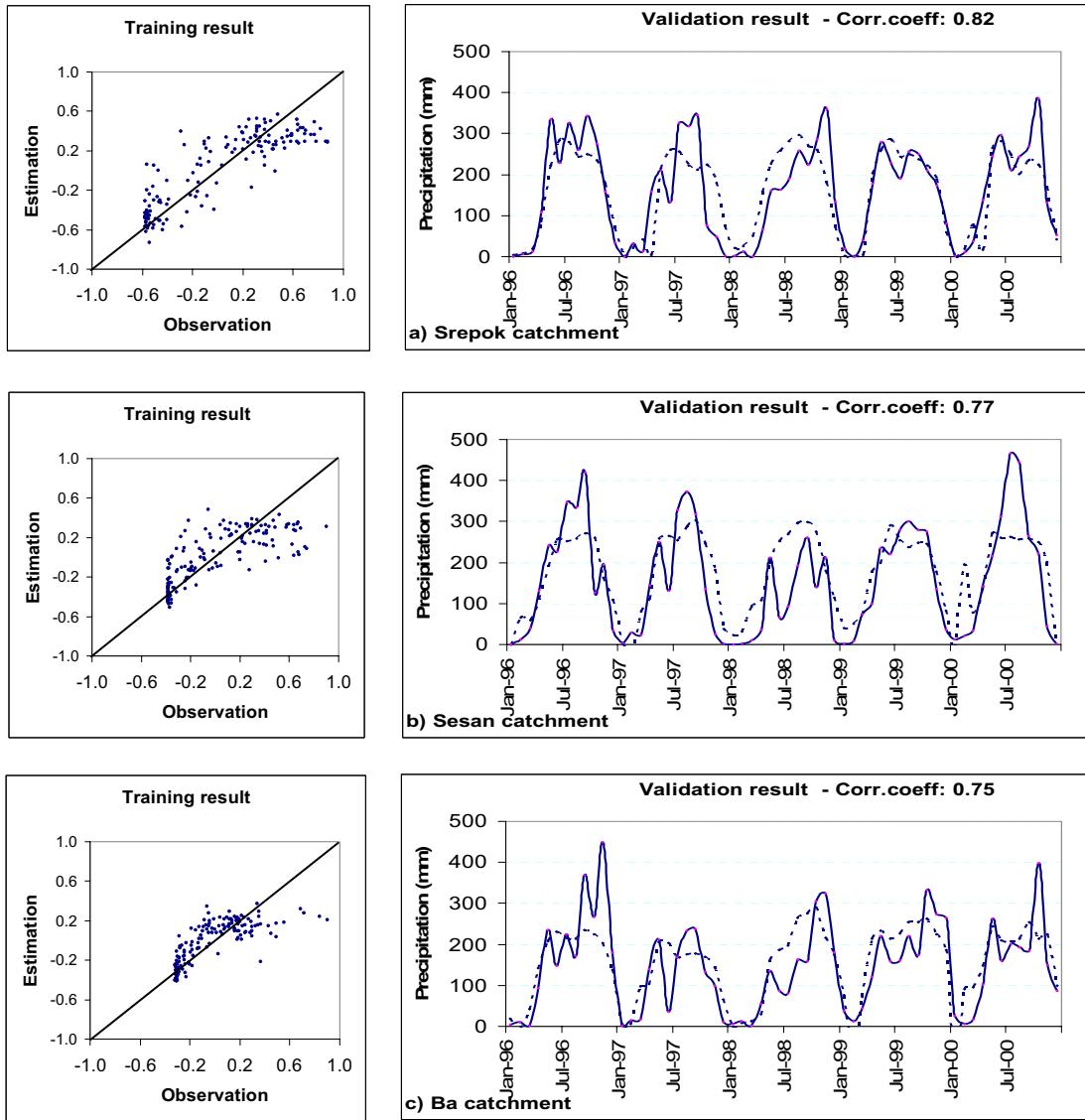

Fig. 5 Forecast results for monthly precipitation obtained from ANN models. Left panels show the training results. Right panels present time series of observed (solid) and estimated (dash) precipitation during the validation period for three catchments.

Likewise the rainfall forecast, discharge forecast results are illustrated in Fig. 6. The scattering of the results for the training period indicates that the models tend to present well the discharge variability. The two-month lag SST in El Niño3 area and the

one-month lag humidity, air temperature and discharge of are used as input to the models. The time series of observed and estimated values are presented in the right panels, and high correlation coefficients are obtained for all three catchments over the VCH, 0.82 for Bandon (Srepok catchment), 0.78 for Kontum (Sesan catchment) and 0.88 for Cungson (Ba catchment).
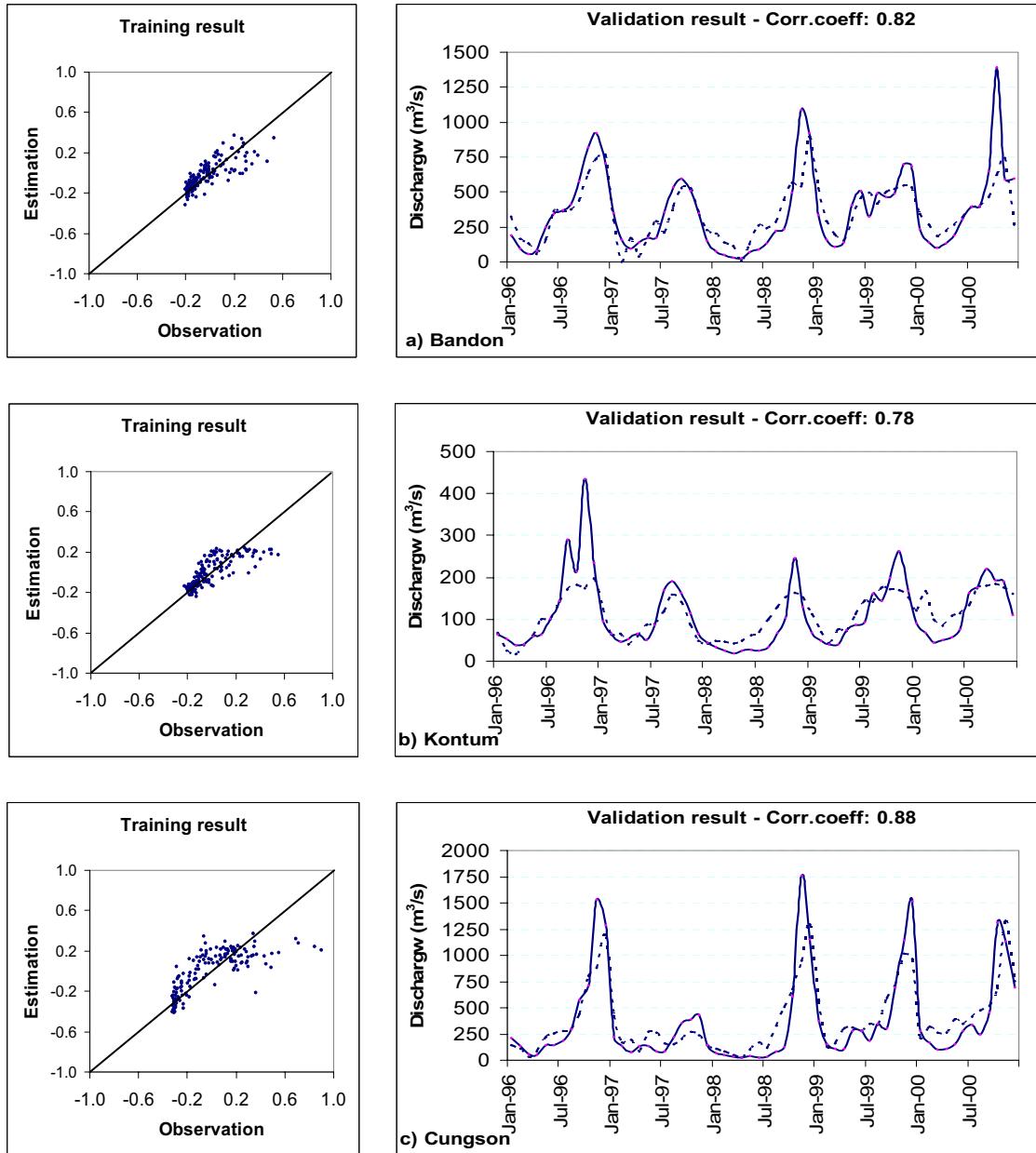

Fig. 6 Forecast results for monthly discharge obtained from ANN models. Left panels show the training results. Right panels present time series of observed (solid) and estimated (dash) discharge during the validation period for sites in three catchments, Bandon (Srepok catchment), Kontum (Sesan catchment) and Cungson (Ba catchment).

The forecasting results for both rainfall and discharge show a very significant role in early drought warning over the VCH. Good performance of models for both forecasts imply that drought indices generated from rainfall or discharge, or a

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combination, can be presented in advance and be combined with real-time monitoring of other hydro-meteorological elements within the region, e.g., water levels in reservoirs, lakes and rivers can provide valuable information on future drought conditions to water managers, decision-makers to help them prepare mitigation and response actions.

III. Drought mitigation and response measures

III.1 Drought response policy and organism

The water law was adopted by the National Socialist Republic Assembly of Vietnam in May 1998, which brings a strong legal power to carry out water resources management. However, legal documents should be continuously improved by decree laws, circular documents, resolutions, processes and norms to reach the best effects of water resources management from governmental to local levels. A drought policy should be concretized with respect to responsibilities and obligations from the governmental level to the local level and especially to citizens affected by droughts. Promulgating a drought policy is fundamental to determining technical norms and assistance to reduce the impacts of droughts through relevant and legal actions, e.g., aid programs, healthcare, low interest loan, subsidies etc. However, the main strategic objectives for drought mitigation and response would be the following methodology for steps developed by *Wilhite [1991]*:

- Establish a specialized drought task force.
- Organize stakeholders to participate in preparation, implement measures and solve conflicts.
- Unify techniques and policy at all levels.
- Determine the drought risk in order to prepare actions for risk mitigation, and minimise the difficulties after a drought occurrence.
- Monitor and assess the implementation of drought mitigation and response measures including mistakes and successes to meet the demand of social economic development.
- Promulgate drought plans and awareness campaigns, and issue timely public information.
- Enhance participation in actions for drought mitigation and response processes.

III.1.1 Principles for a drought policy

A drought response policy is a list of relevant actions to be taken in association with drought impact mitigation. The possible actions for dealing with droughts in terms of internal operation and water resources management in an institutional and legal framework are discussed and adopted by the highest legal competences. Monitoring intensification and inspection of facilities to safeguard the rules for infrastructure operation will be needed for internal operation. Regarding water resources management,

the possible actions should comprise stakeholders seeking, information dissemination on encouragement to enforce water savings, restriction of certain uses, and focusing on water resources conservation and environment protection. From the institutional perspective, a drought committee needs to be appointed to address specific issues and overcome challenges to enhance collaboration of agencies, organizations and stakeholders. A number of legislative measures should be adopted for emergency cases of extreme droughts with possible palliative measures such as explaining pricing and restriction of water uses, aid programs, healthcare etc.

Different options of measures taken would lead to different effectiveness and imply multiple impacts on economic and social sectors [*Wilhite 1997b*]. Only certain measures are fully feasible and potentially effective in a certain drought situation. Therefore, from the management perspectives, drought mitigation and response strategies are presented in three scenarios corresponding to thresholds indicating the severity in terms of both hydrological and meteorological indices, as illustrated in Table 7. The informative indicators are useful to identify and characterize drought occurrences. However, more indicators would be helpful for water managers and decision-makers to determine the occurrence of the phenomenon and its effects, e.g., evapotranspiration and soil moisture and their trends.

Table 7 Drought scenarios based on drought indices thresholds

Drought scenario	SPI	SWSI	Drought severity
Pre-alert	-1.0 to -1.49	-2.0 to -2.99	moderate
Alert	-1.5 to -1.99	-3.0 to -4.0	severe
Emergency	-2.0 and below	-4.0 and below	extreme

Major elements in a drought policy have been described by *Grastang [2002], Wilhite [1991]* and *Garrote et al. [2005].* This information is available at the website of the U.S National Drought Mitigation Centre and found appropriate and feasible for application in Vietnam. The following scenario description is based on the above mentioned references.

Pre-alert scenario: When the SPI value reads -1.0 to -1.49, and monitoring shows that discharge continuously reduces and may lead to SWSI values in the range between -2.0 to -2.99 corresponding to moderate shortage of water supply and the initial stage of drought development, pre-alert scenario is declared. The main objective of management in the pre-alert scenario is to prepare appropriate actions for the possibility of a drought. The drought assessment committee needs to be activated to evaluate the future scenarios and recommend appropriate actions for any scenarios. The potential impacts on environmental, economic and social sectors need to be assessed and water conservation goals set to mitigate the potential impacts. The public should be informed to get acceptance of measures that would be taken, if the drought intensity increases.

Another goal is to prepare organisations and stakeholders for implementation of restrictions with focus on communication and awareness. Non-structural measures are generally taken in order to reduce water demand, and to avoid alert situations.

Alert scenario: The alert scenario is declared when the SPI reads -1.5 to -1.99, and monitoring shows that discharge continuously reduces and that the SWSI may fall below -3.0, which means that water supplies are significantly lower than demand and a severe drought occurs that probably will have environmental, economic and social impacts in the future, if possible measures are not taken. The drought assessment committee should issue water shortage statements, inform the public and set more stringent conservation goals. The drought mitigation and response committee is activated to implement an educational effort to encourage voluntary conservation of all water uses and incorporate enforceable restrictions of non-essential water uses that do not affect drinking water, or water exchange between uses. The possible actions are taken in order to avoid a drought emergency situation by enacting water conservation policies and mobilizing additional water supplies. These measures are coercive to stakeholders, but in this situation water supply for higher priority uses should be guaranteed. This may cause conflicts between water users due to overruled user rights.

Emergency scenario: When the SPI reads below -2.0 and monitoring shows that discharge continuously reduces and the SWSI reads below -4.0, the occurrence of an extreme drought with huge shortage of water supplies is present, which has strong impacts on the environmental, economic and social sectors, and water supply even for higher priority uses is not guaranteed, if drought continues. An emergency situation is declared, and the main objective of management is to mitigate impacts and minimize damages of the drought. The drought assessment committee should inform the public through public media, especially to direct water users. The drought mitigation and response committee needs to implement measures immediately to reduce water usage of all uses. The minimum water requirement for crops is a considerable priority and should be satisfied. Mandatory allocation of water to communities should be started, as drinking water requirements is considered a high priority that must be satisfied. Set a maximum allowable usage and increase pricing on water use by charging higher rate per unit to all water users. The actions taken in an emergency case should be direct and restrictive due to their high economic and social implications, and some legal exceptional measures should be used in this situation such as subsidies, low-interest loans for water users, and aid programs should be activated to alleviate starvation and prevent diseases for residents living in the area affected by drought.

III.1.2 Implementation organization framework

A drought committee is necessarily appointed to supervise and coordinate development of drought planning corresponding to the multidisciplinary nature of drought and its impacts. During drought occurrence, the drought committee should

work closely with public media to keep the public well-informed of the water supply status and drought condition that may lead to requests for voluntary or mandatory use restrictions. The committee should have access to assistance from other governmental agencies and organizations including international and non-governmental organizations. In general, a drought task force comprises a monitoring committee, an assessment committee, and a mitigation and response committee as proposed by *Wilhite et al. [2000]* and presented in Fig. 7. The monitoring and assessment committees are responsible for reporting the occurrence and severity of the drought and its impacts on sectors, and recommending mitigation and response actions to the drought committee, then the mitigation and response committee is assigned (if necessary) to implement actions to reduce drought impacts. The activities on mitigation and response should be implemented by a close cooperation among localities, ministries, organizations, universities and institutions. Workshops and conferences should be annually held at national or provincial levels to assess the operation of the drought task force, and reports should be delivered to all participants and related organizations to ensure that follow-up activities will be cooperative and efficient. The members of the drought committee should include appropriate representatives of various governmental agencies, key stakeholders, relevant research institutes and universities, where appropriate specialized experts are available. Thus, it is potentially in a position to make recommendations to appropriate political leaders, and to implement mitigation actions and request assistance from various governmental agencies and other organizations to make the implementation of measures more efficient in the mitigation and response process.

The drought committee needs to appoint a chairman and a vice-chairman to operate the system from the national to the local level. The chairman and vice chairman have responsibility to develop an operation agenda of the drought committee to collaborate with related governmental agencies and localities in elaborating and adopting the drought mitigation and response plan. They are mainly responsible for operating the drought committee and cooperating with other agencies and organizations in implementation of the drought mitigation and response programme. The chairman should be a representative for the most directly affected sectors. The members of the drought committee at the national level should be representatives of ministries and each ministry has its own responsibilities, and appointed based on the decree 91/2002/ND-CP in terms of duties and rights for water resources management:

- Ministry of Natural Resources and Environment (MONRE) (appoints the chairman)
- Monitoring and forecasting water availability and setting up database
- Elaborating guidelines and regulations for implementation of measures for water resources and environment protection
- Inventory and assessment of natural resources

- Ministry of Agriculture and Rural Development (MARD) (appoints the vice-chairman)
  - Exploitation and use of water resources under the approved guidelines and regulations
  - Design, construction and protection of hydraulic works for water supplies in terms of irrigation, drainage and drinking water in rural areas.
  - Planning and development of appropriate crop patterns supporting the water resources strategy and sustainable development
- Ministry of Planning and Investment
  - Guiding and checking in relation to planning and implementation of the social-economic development strategy of ministries
  - Developing strategies and polices in terms of investments related to water resources development and environment protection
- Ministry of Science and Technology
  - Developing and providing water quality standards for different water uses
- Ministry of Fisheries
  - Management and exploitation of water resources used for aquaculture
  - Planning and development of aquaculture resources in support of environment protection and sustainable development
- Ministry of Construction
  - Planning and management of water supply projects in urban areas and industrial zones
- Ministry of Industry
  - Developing hydropower plans and guidelines for operation of hydraulic works
- Ministry of Transportation
  - Managing water used for river navigation
- Ministry of Health
  - Managing drinking water quality and monitoring water quality standards
  - Public healthcare and sanitation
- Ministry of Culture and Information
  - Managing water resources used for recreation and tourism services
  - In combination with other ministries providing information to public, timely and precisely
- Research Institutes, Universities of relevant ministries
  - Providing researchers and experts to advise and transfer technology to relevant fields

The drought committee at the provincial level acts as a sub-committee under the guidelines and assistance of the national drought committee. It is responsible for

providing most technical staffs in each working group that get assistance from specialists, researchers from relevant ministries, institutes and universities to prepare and carry out measures related to mitigation and response. The members are representatives of departments belonging to relevant ministries.
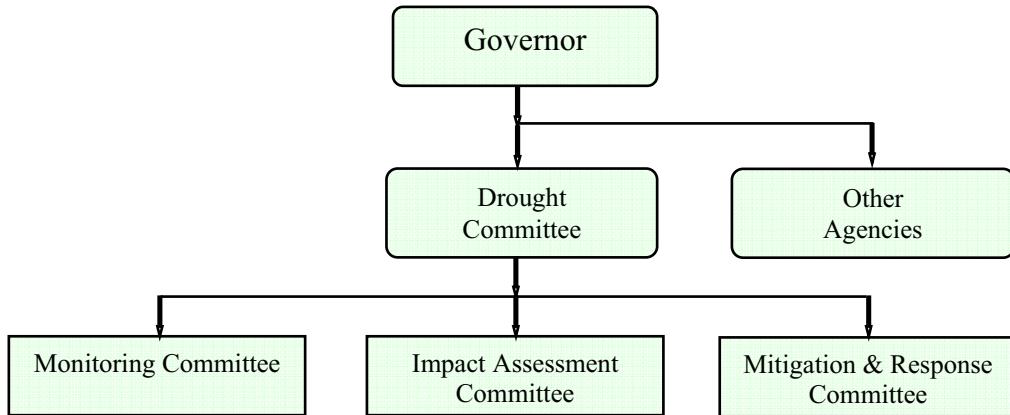

Fig. 7 Proposal for the drought committee organizational structure (source *Wilhite et al. 2000*)

A proposal for a drought committee has been comprehensively presented in *Wilhite et al. [2000]* and *Grastang [2002].* Additional information is found in *Wilhite et al. [1991]* and *Wilhite et al. [2005].* The below proposal for the structure of a drought committee in Vietnam is based on these references.

Monitoring committee: The monitoring committee is built up by a group of technical staffs belonging to the relevant HMS agency and is responsible for monitoring and providing short and long-term outlook of water availability and climate variables such as precipitation, temperature, evaporation, stream flow, groundwater level, reservoir levels etc. These monitored elements might be used to simulate drought indices to visualize drought occurrence and reflect impacts on agriculture, households, industry, transportation, recreation and tourism etc. On this basis evaluation reports assessing the water availability situation and providing an outlook should be issued. The reports should be prepared and disseminated to the drought committee, relevant governmental agencies and the public media. The monitoring committee should work closely with public information specialists to keep the public well informed about changing conditions.

Impact assessment committee: The impact assessment committee is composed of local technical work groups assisted by specialists from relevant research institutes, universities and ministries. It is responsible for identifying and assessing significant drought impacts on the environmental, economic and social sectors, and recommending appropriate and reasonable mitigation measures to the drought committee. The analyses, findings, and data dissemination of current and post drought events must be reported to the drought committee. The number of working groups depends on economy and society mechanisms, the more complex economy and society, the larger number of

working groups. Generally, working groups are formed and in charge of assessments as presented in *Bradford et al. [2000]*:

Economic impacts

- Annual and perennial crop losses
- Damage quality and reduce productivity of crops
- Damage to fishery production and wildlife habitats
- Insect infestation and plant disease
- High cost or unavailability of water for livestock, households
- High livestock mortality rate
- Losses to recreational services and tourism industry
- High cost of water supply, energy
- Revenue losses to government due to tax base reduced

Environmental impacts

- Damage to plant species
- Increased number and severity of fires
- Loss of wetlands, forests
- Decreased groundwater level, land subsidence
- Loss of bio-diversity
- Soils erosion
- Reduced water level of reservoirs and lakes
- Water quality effects (increase of water temperature, dissolved oxygen)
- Air quality effects (dust, pollutants)

Social impacts

- Mental and physical stress
- Health problems due to pollutant concentrations, diseases etc
- Increased diseases caused by wildlife concentrations
- Increased poverty
- Loss of human life due to heat stress, famine, diseases
- Increased conflicts (water users conflicts, management conflicts etc)
- Reduced quality of life or changes of lifestyle
- Population migration (e.g., from rural to urban areas)

However, the Vietnamese working groups may in particular focus on the following affected sectors in the VCH due to its uncomplicated economy and society mechanism:

- Agriculture: livestock, annual and perennial crops, agricultural productions
- Natural resources and environment: fishery, forest fires, aquifers, land erosion, landscapes
- Water supply: drinking water, irrigation, public uses, households, industry
- Recreation: tourism, river navigation
- Energy: hydropower production

- Health: human health problems due to pollutant concentrations, diseases associated with water contamination
- Economy: personal incomes, business, governmental tax
- Communication and conflicts: public communications, water user conflicts

Moreover, the impact assessment committee is also responsible for evaluating and analyzing the successes and mistakes in collaboration with the committees, governmental agencies and non-governmental organizations through the post drought, as well as making recommendations to the drought committee to ensure the mechanisms to be more innovative and responsive.

Mitigation and Response committee: The mitigation and response committee is composed of local authorities, stakeholders and assistance from specialists, governmental agencies and organizations. It has responsibility to implement the mitigation and response actions to reduce drought impacts, and proposes a cost estimate for these actions and report to the drought committee. The funding for these actions would be sought through various governmental and non-governmental agencies. It should work in collaboration with monitoring and impact assessment committees to keep the public well informed about drought conditions, and prepare appropriate response actions. The members of mitigation and response committee should have knowledge and experience to understand drought mitigation techniques, risk on sectors, and decision-making processes at any levels. The number of appropriate actions depends on drought severity, affected sectors and the exposures of vulnerability of sectors to drought events, which are identified and included in the report of the impact assessment committee.

Localities participation: The local authorities such as districts and communities should be main actors to implement mitigation and response actions at the field level following the guidelines of the drought committee. They take the main responsibility to identify activities and priority areas to implement appropriate actions. It monitors and participates in evaluation of efficiency of mitigation and response implementation processes. Also, it makes suggestions on solutions and provides feed-back information to the drought task force.

III.2 Implementation solutions

The water law was adopted by the National Socialist Republic Assembly of Vietnam in May 1998 in terms of water resources management, and the decree 91/2002/ND-CP in terms of duties and rights for implementation of solutions in relation to water resources management. This following section is based on the legal documents and others references related to the topic including *Hieu[2002], Thanh[2002], Hoc[2002]* and *NAP[2002]*.

III.2.1 Water resources management

Agriculture and some other major economic sectors that are affected by droughts are faced with the deficit of water availability over Vietnam in general and particularly over the VCH. Drought mitigation measures need to apply an integrated approach based on using the most suitable drought-resistant crops with minimum water demand and a better management and regulation of water distribution [*Hieu 2002*]. Drought mitigation measures should include a comprehensive survey and evaluation on water resources management. The main objective of water management is to supply enough water in terms of both quality and quantity for livelihood, production and promote sustainable usage of the water resources.

Structural measures: Water development planning in each basin, irrigation and drainage system must be based on water demands for living, economy, and environment protection. The structural measures play a very important role in water allocation and water supply due to the complex topography, temporal and spatial rainfall distribution, and varying water demand [*Thanh 2002*].

- Reservoir development is the most important to warrant the water security for cultivation, living, and environment over the VCH. Amongst others, improving the storage capacity of available reservoirs and building new ones to recharge the groundwater, keeping surface water and reduce evaporation need to be considered and implemented to enhance the ability of water regulation throughout the rainy and dry seasons.

- Mobile pumping shows its effectiveness to alleviate drought when irrigation systems are not fully developed. Determination of the quantity and capacity of the pumps in an area, or in an irrigation system, depends on the area regularly affected by droughts, the volume of water that can be used, the topography, and the average duration of droughts.

- Water usage coefficients of irrigation systems are in the interval 0.5 to 0.65 due to high losses by infiltration and evaporation, where water is being transported and/or used. Therefore, improvement of existing irrigation systems including infrastructures and irrigation technologies should be implemented to reduce the above losses in order to improve the water usage coefficient. High technologies can be introduced including sprinkling, leaching, and underground watering. However, these technologies are relatively expensive and considerably used only for high yield cash crops.

- Upgrade the capacity of water supply systems available and establish necessary new ones for industry, public uses and especially for households, drinking water to meet the increasing demand in both quantity and quality due to economy development and population increase.

Non-Structural measures: Besides the structural measures of water resources development and management for dealing with water deficit, non-structural measures are essential and helpful in supplement to strong effectiveness of water resources development and management and economic development plans. The non-structural measures can be grouped as proposed by *Hieu [2002]*:

- Identification of plant types, crop schedules, and cultivation methods aims at reducing water demand, utilizing effectively water availability, and enhancing soil reclamation. Transformation and multiplication plant systems need to be identified using optimization models, which are developed based on the strategy and local conditions, e.g., cultivation area, water supply, food security, and commodity trading. The optimum answer can be assisted with the use of a computer model for management science software (CMMS), which is widely used in many countries.

- Community management and education promote participatory irrigation management focusing on best practices in irrigation and water resource management, lessons learned, training materials and networking through all levels among professionals, researchers, policy makers and farmers. Also, it promotes water use saving knowledge to water users in terms of guidelines on how to use water effectively and economically.

- Forest plantation and protection planning should be immediately approved by the government, and then forest land allocation can be allocated, under the Land Law and the Law on forest protection, to households, cooperatives and organizations for permanent agricultural and forestry production purposes to prevent land degradation, soil erosion and improve water regulation within the hydrological cycle to reservoirs and lakes.

III.2.2 Science and technology promotion policy

It is essential to strengthen research in science and technology, and enhance technology transfer activities to support and solve issues that are critical for society development. The results of increased funding for research institutes and universities should be shared among research agencies and should become more demand oriented with respect to both technique and management in relation to sustainable water resources development in general, and particularly for drought preparedness and mitigation actions.

III.2.3 Training and education promotion

It is necessary to train the management and technical staffs, especially at the local level, to ensure that adequate knowledge and skills become more efficiently involved in all activities of the drought preparedness and mitigation process. Training and education should focus on priorities for local capacity building:

- Strengthen capacity in planning and management in terms of water resources
- Promote knowledge on roles of water availability, environment protection and sustainable development
- Improve capacity of drought monitoring, impacts assessment, and mitigation and response

III.2.4 Communication and information channel enhancement

An effective communication mechanism is essential to implementation of the drought task force in terms of disseminating and sharing information, knowledge and experiences within sectors and among sectors, regions, countries and international organizations. The mechanism should focus on approaches:

- The communication should be strategic and targeted with an emphasis on quality over quantity. It should focus on priority issues of the drought task force implementation process, the needs of major stakeholders, environment protection, and sustainable development.
- Establishment of effective networking partnership among sectors and organizations to achieve the best efficiency. The network should be strongly connected and aware of existing information and convey relevant knowledge of the drought task force implementation process to partners.
- Establishment of a feed back system where the partners can express what communication services are most effective or what are the remains in implementation process to ensure the drought task force to be gradually more innovative and responsive to meet varying and evolving information needs from partners and public.

III.2.5 Partnership and arrangement promotion

The drought task force, as any other action programs, needs a combined approach to mitigation of drought, poverty alleviation and sustainable development. This should be considered very carefully in the implementation process. Thus it is essential to include partnership arrangement in the drought task force implementation. By collaborating, the partners aim to maximise effectiveness and efficiency in mobilization and use of all the resources applied to mitigate drought impacts. So, partnership is one of the effective tools for mobilization of available resources and strengthening cooperation among agencies and organizations in drought mitigation and response implementation to lessen drought impacts, to protect environment and approach sustainable development.

IV. Conclusion

Drought occurs regularly in Vietnam at any time even in the rainy season, although it mostly occurs at the end of dry season, especially over the central highlands

in recent years, which causes potential damage to both livelihood and economic development as other natural hazards such as floods, typhoons, storms. Contrary to these hazards, droughts are very difficult to recognize due to its creeping development characteristics. Drought in Vietnam has been a concern for the government and scientists in recent years, and is now attracting the attention of public media once it occurs. There is still no official drought task force committee despite a national committee for flood and storm prevention has been established and has achieved significant successes in dealing with damage and its consequent impacts on the economic and social sectors. So, it is very essential to establish a drought committee to deal with diverse drought impacts on the environmental, economic and social sectors, and approach sustainable development. A comprehensive drought policy needs to be elaborated and adopted by the highest political competence to apply in the drought preparedness and mitigation process. Drought mitigation and response policy needs to be combined with other implementation solutions in terms of water resources management, science and technology promotion, training and education, communication and information enhancement, and especially partnership and arrangement to reinforce the drought task force dealing with impacts on affected sectors and enhance sustainable development.

Drought issues are a national concern, so the implementation of measures needs to be taken in synchrony from the governmental to the local level, combined with seeking assistance from international and non-governmental organizations in terms of funding and technologies. The role of management is obvious in implementation of measures for drought preparedness and mitigation. A good management system is the result of appropriate policy and institutional development and can lead to reduction of the risk of water shortage, subsequently lessen drought impacts and eventually to sustainable development.

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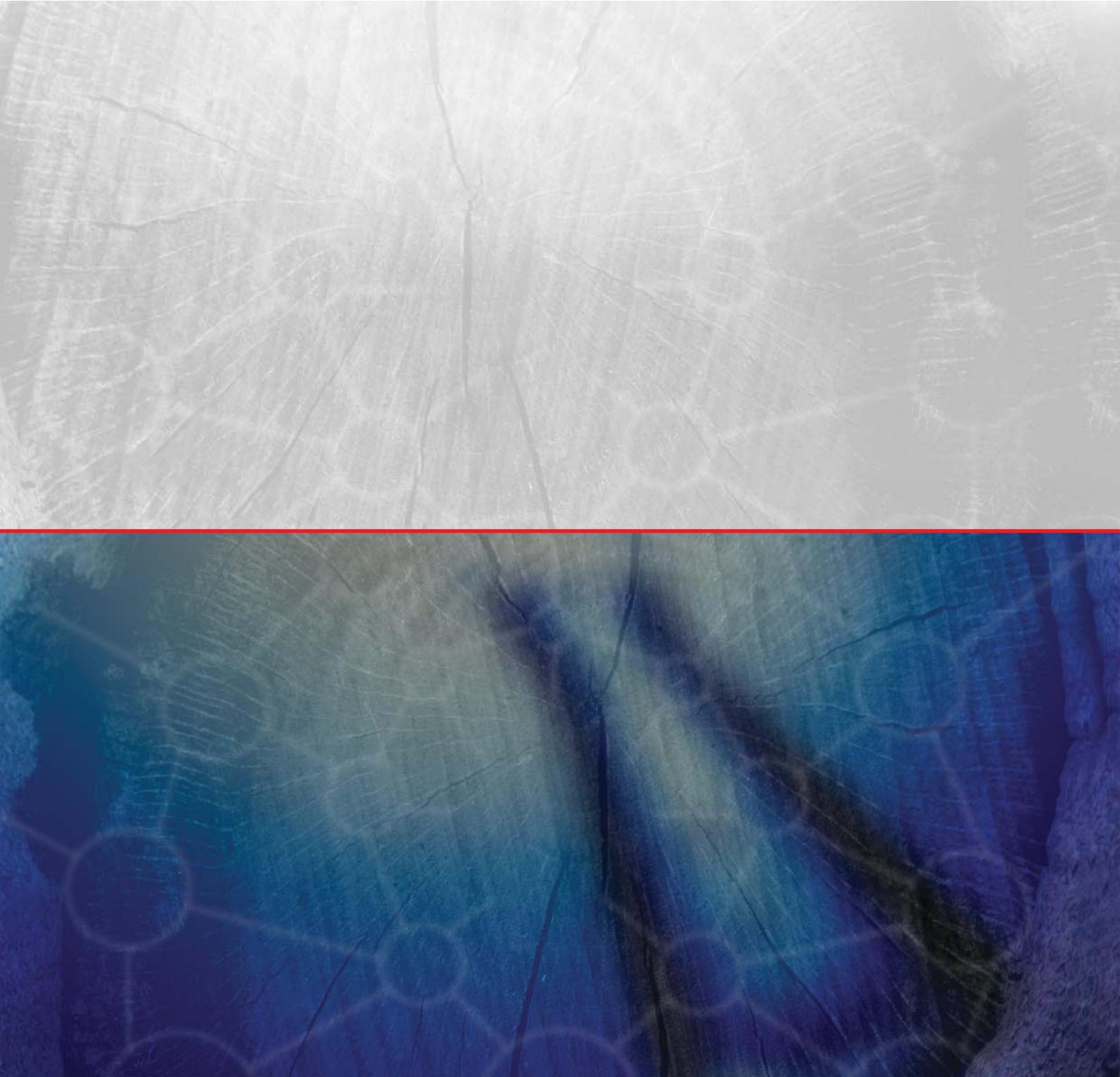
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