Regional Technical Workshop on Application of Modelling Tools for Climate Change Impact and Vulnerability Assessment

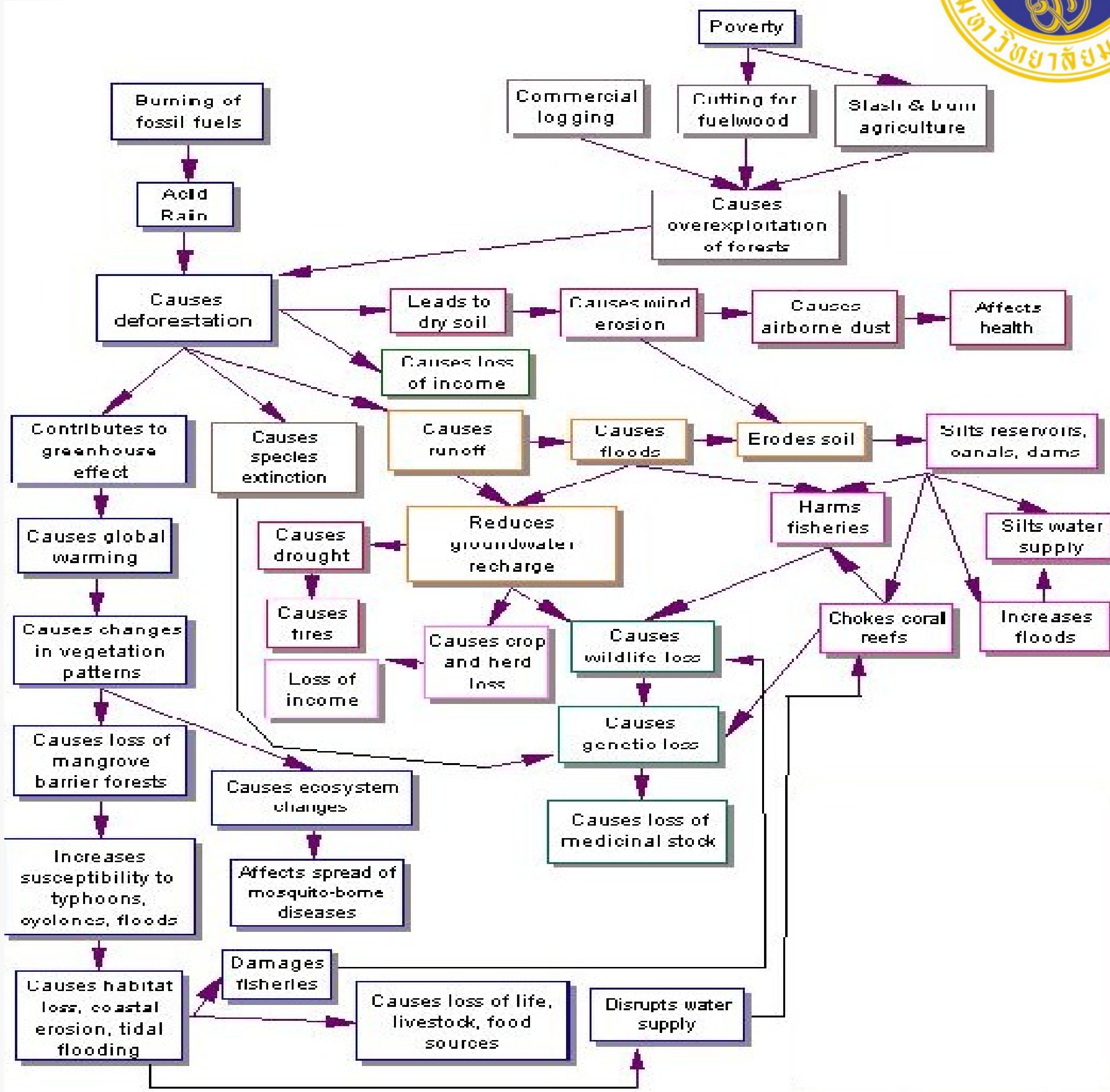
Irrigation/Water Modeling Against Real Time Climate Extreme Cases

Kampanad Bhaktikul Assoc.Prof.PhD.

Mahidol University

Multiple Causes and Effects

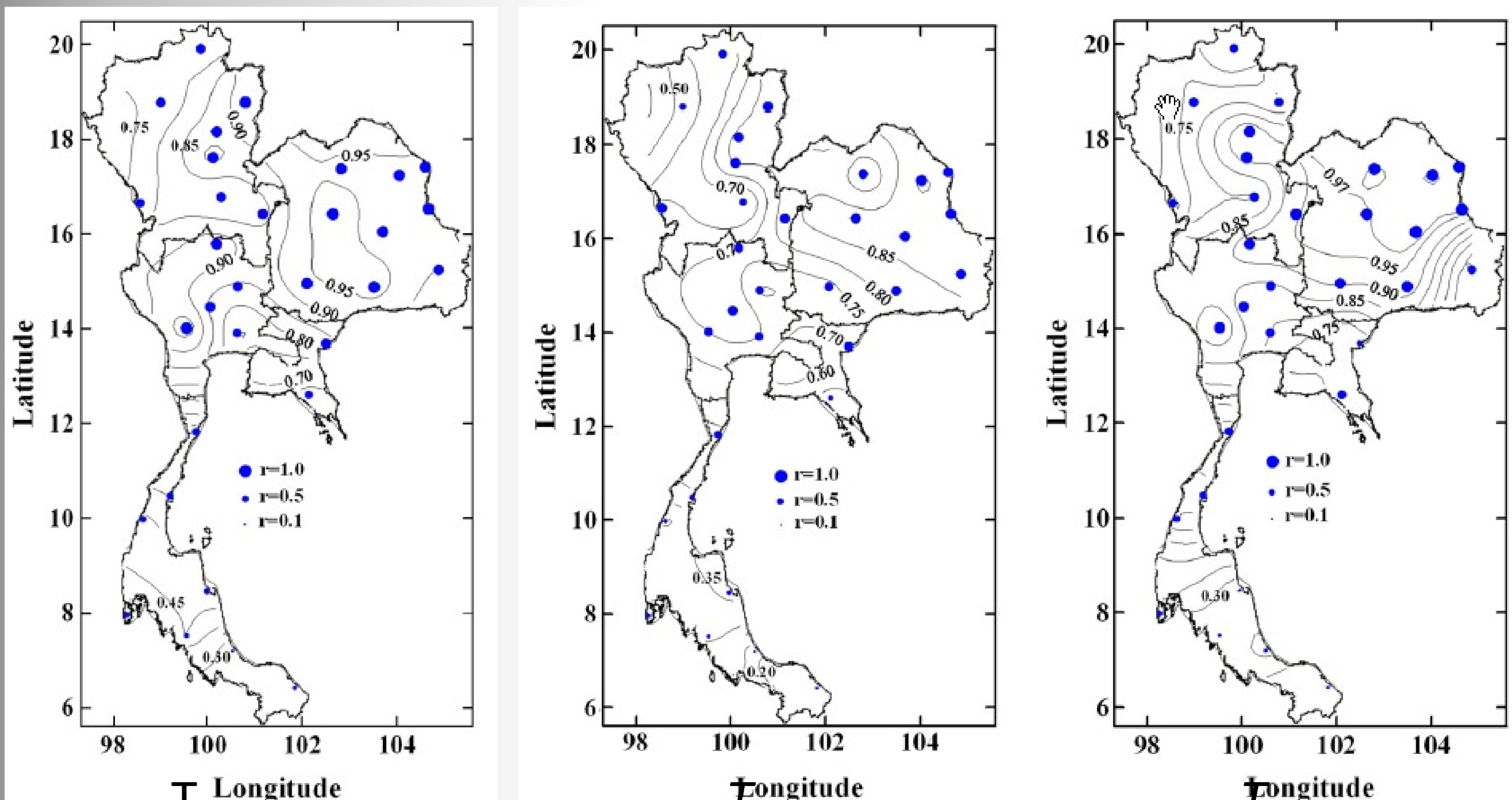
There are multiples causes and effects to the changes in sub-basins that occur from other sources such as human induced, infrastructures development, and present and future economic corridors linking to LMB.



Climate change, variability and extremes

Source: Limsakul and Goes (2008)

Variability in Surface Air Temperatures

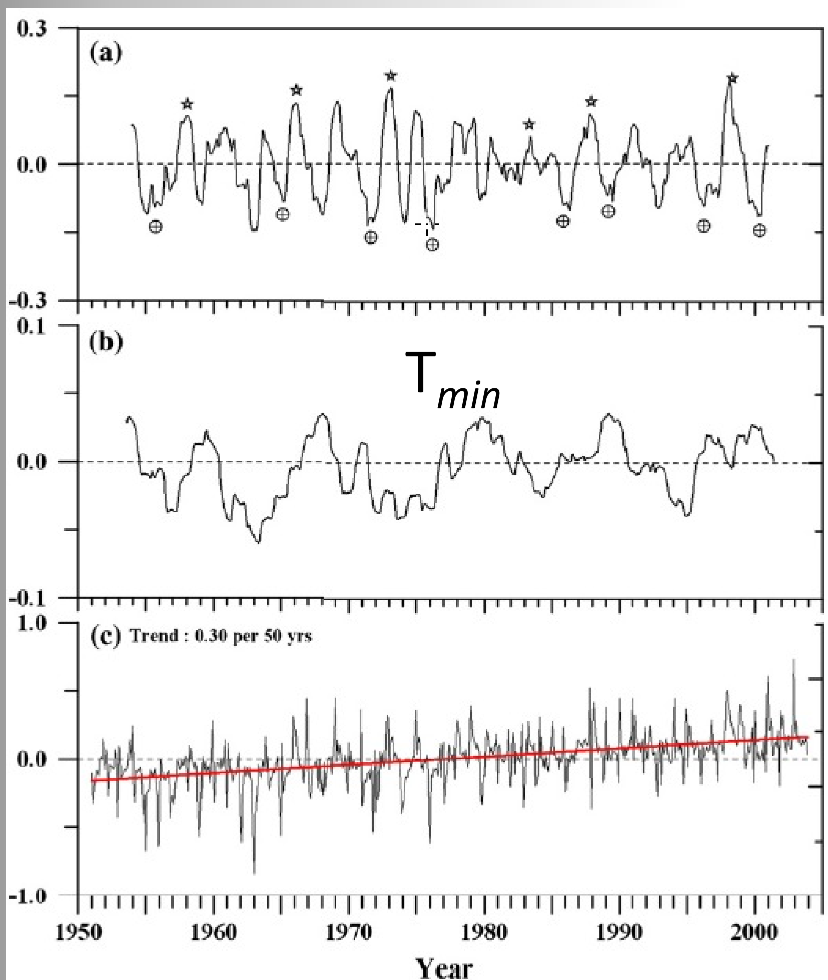


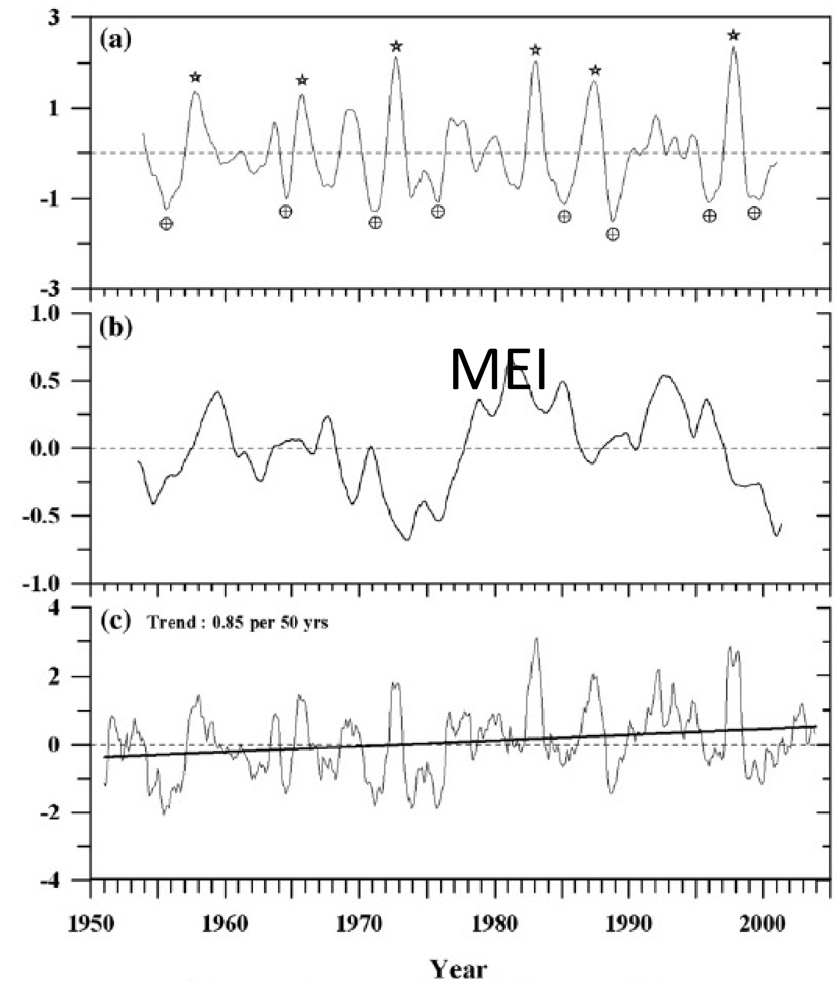
T_{max} T_{mean} T_{min}

The results can contribute to better preparation for future climate research and prediction by providing data for model construction and validation.

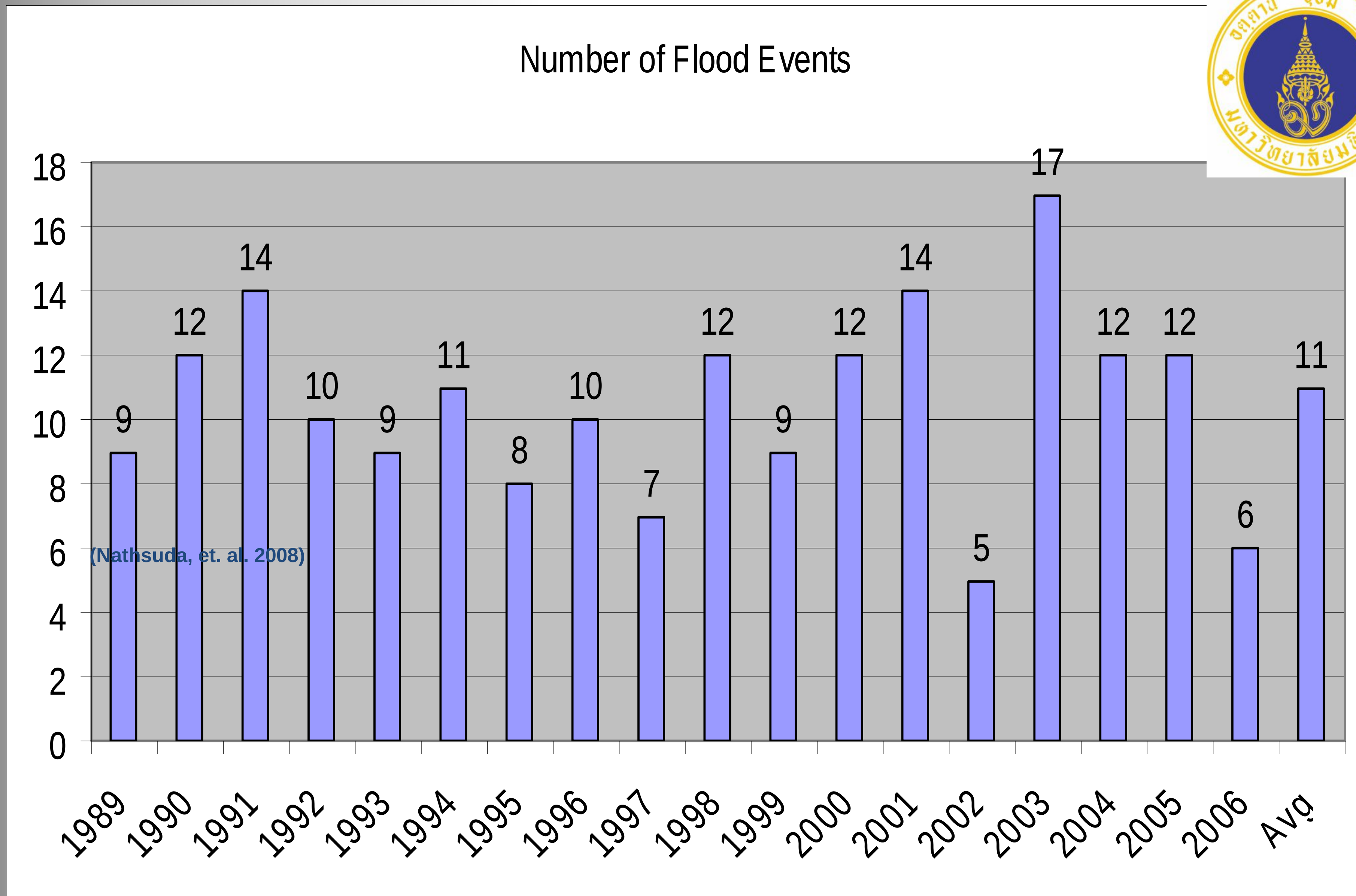
Climate change, variability and extremes

Decadal variability of T_{min} and Multivariate ENSO Index (MEI)

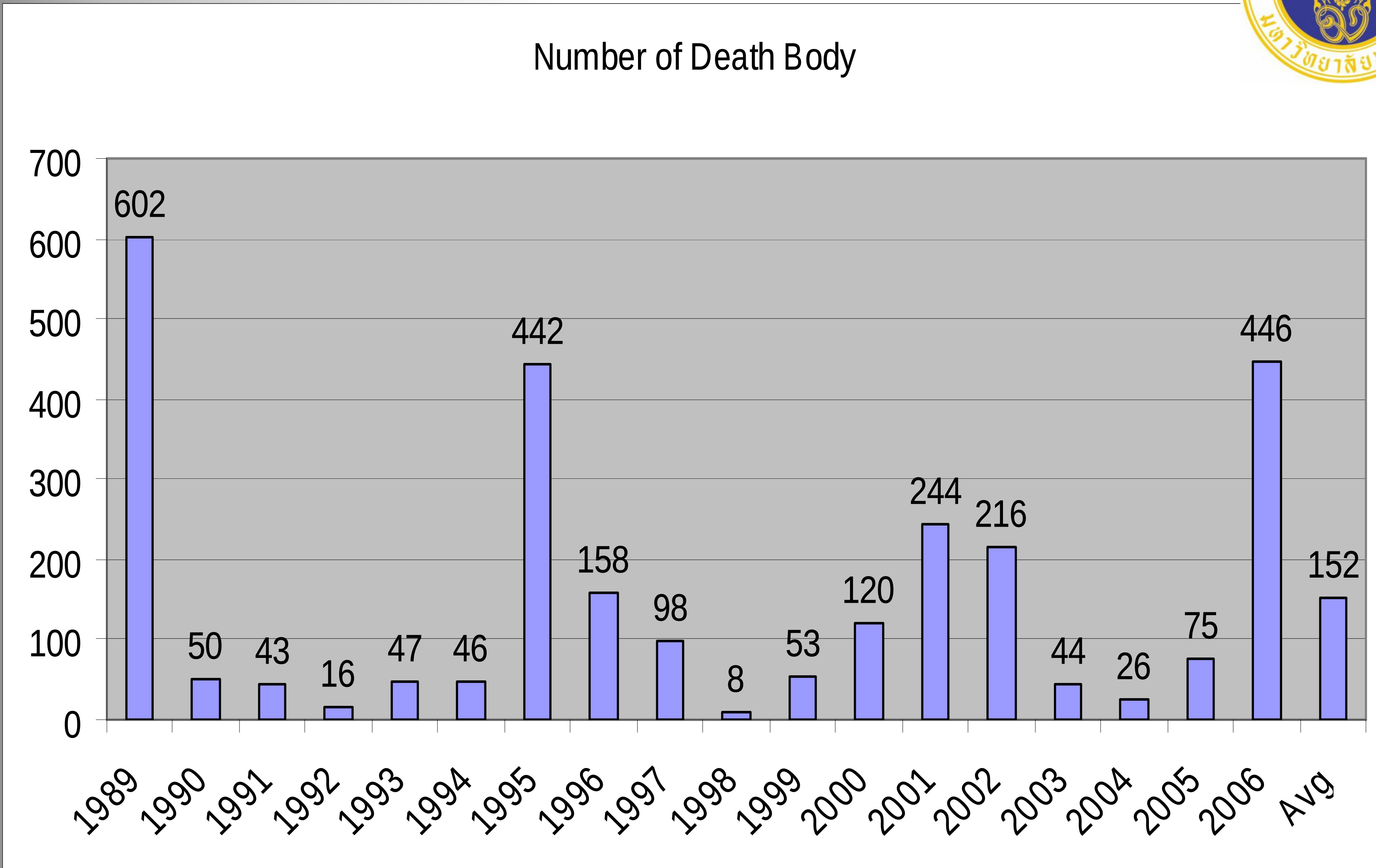




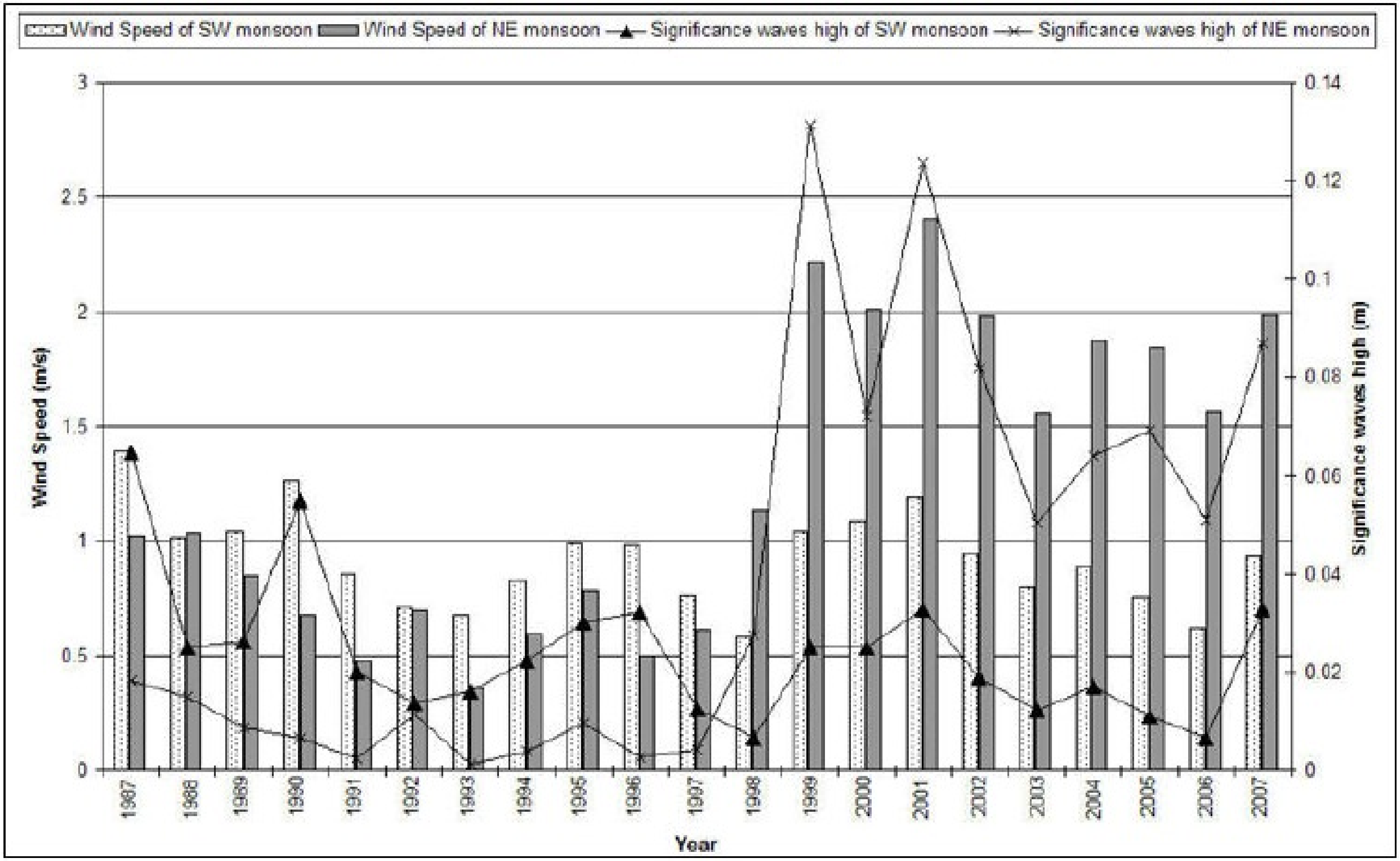
Source: Limsakul and Goes (2008)



Wind speed and waves high, by SW and NE monsoon during 1987-2007 THAILAND

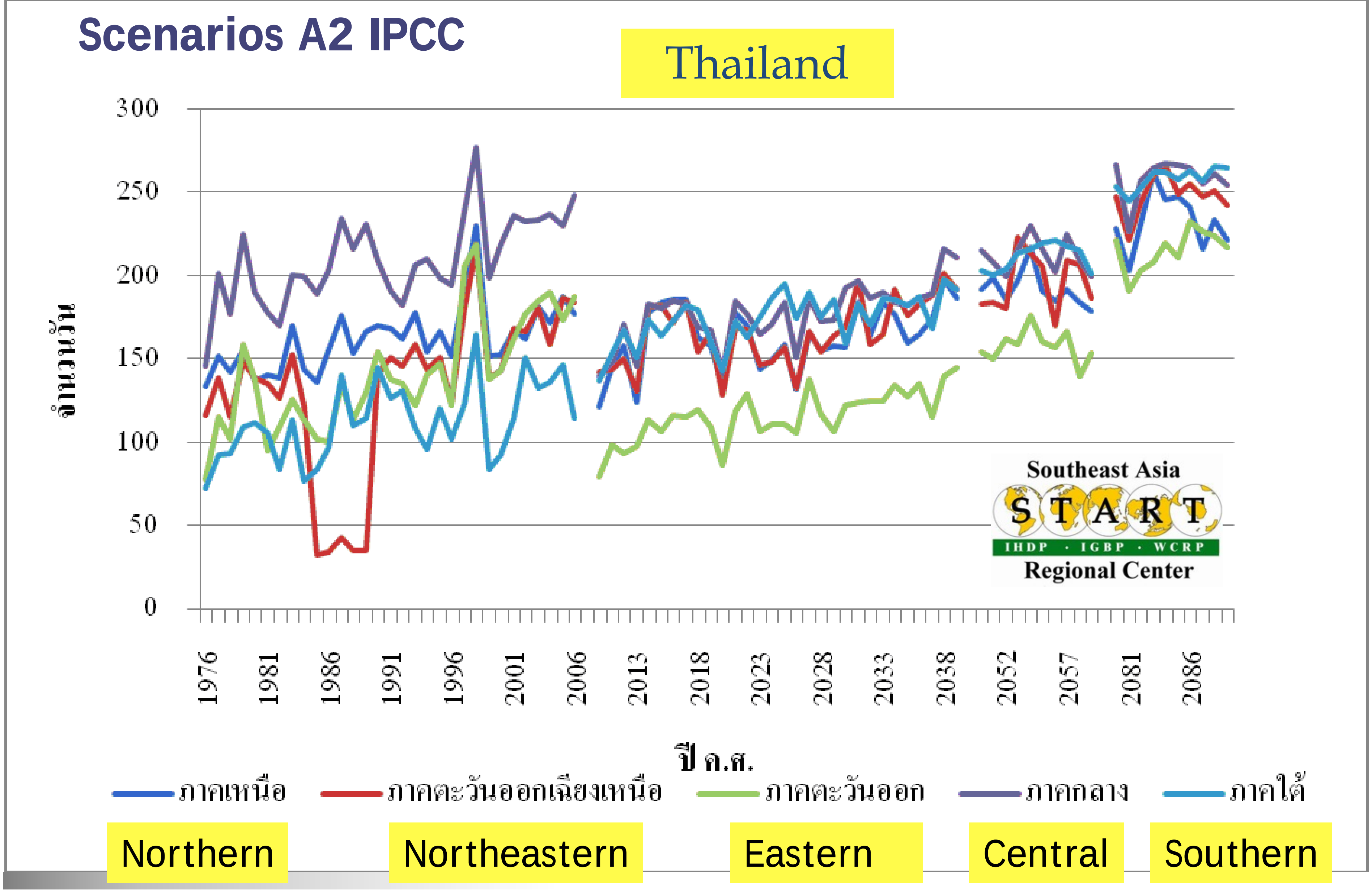


Number of Death Body
700
600
500
400
300
200
100
0
602
50
43
16
47
46
442
158
98
8
53
120
244
216
44
26
75
446
152
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Avg

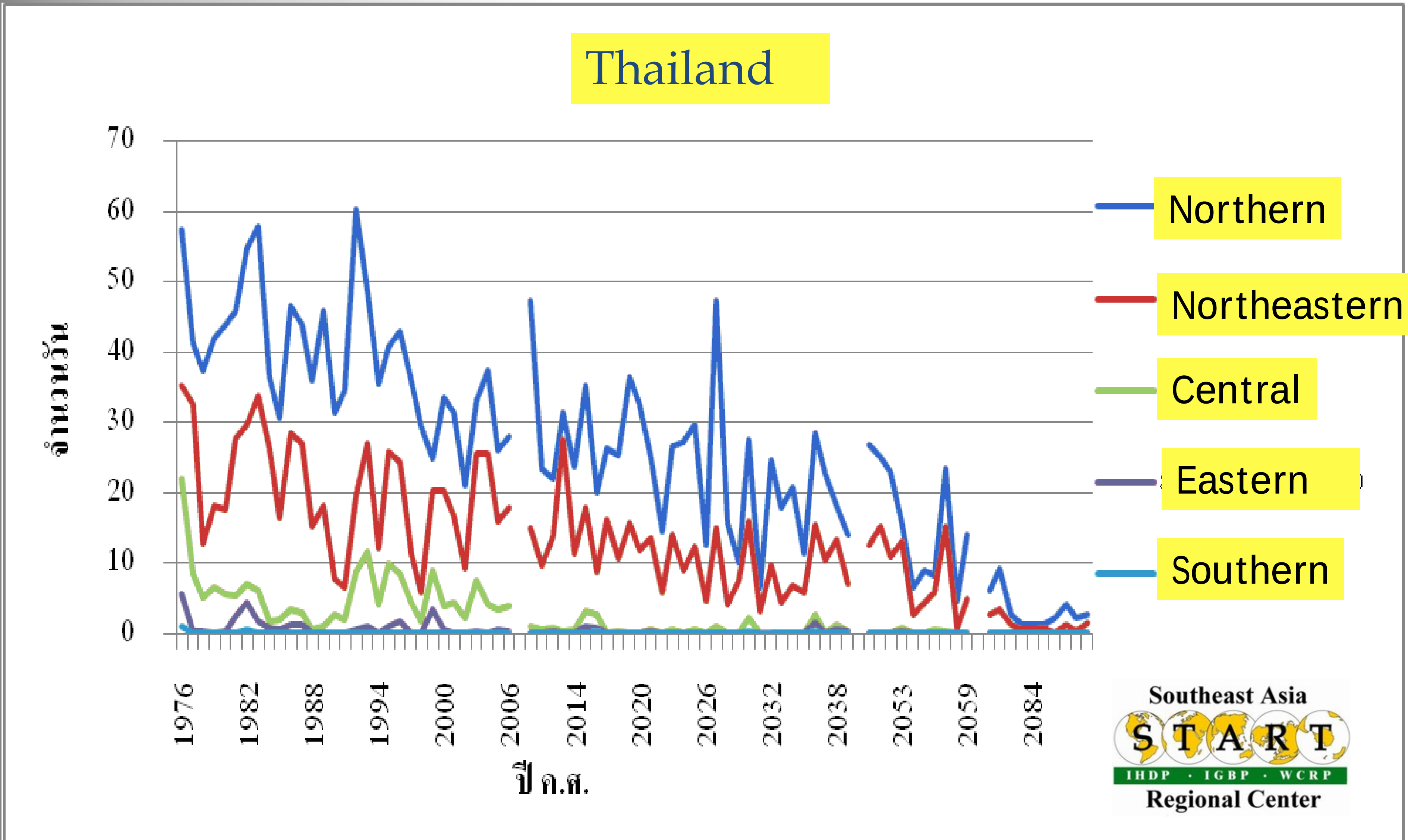


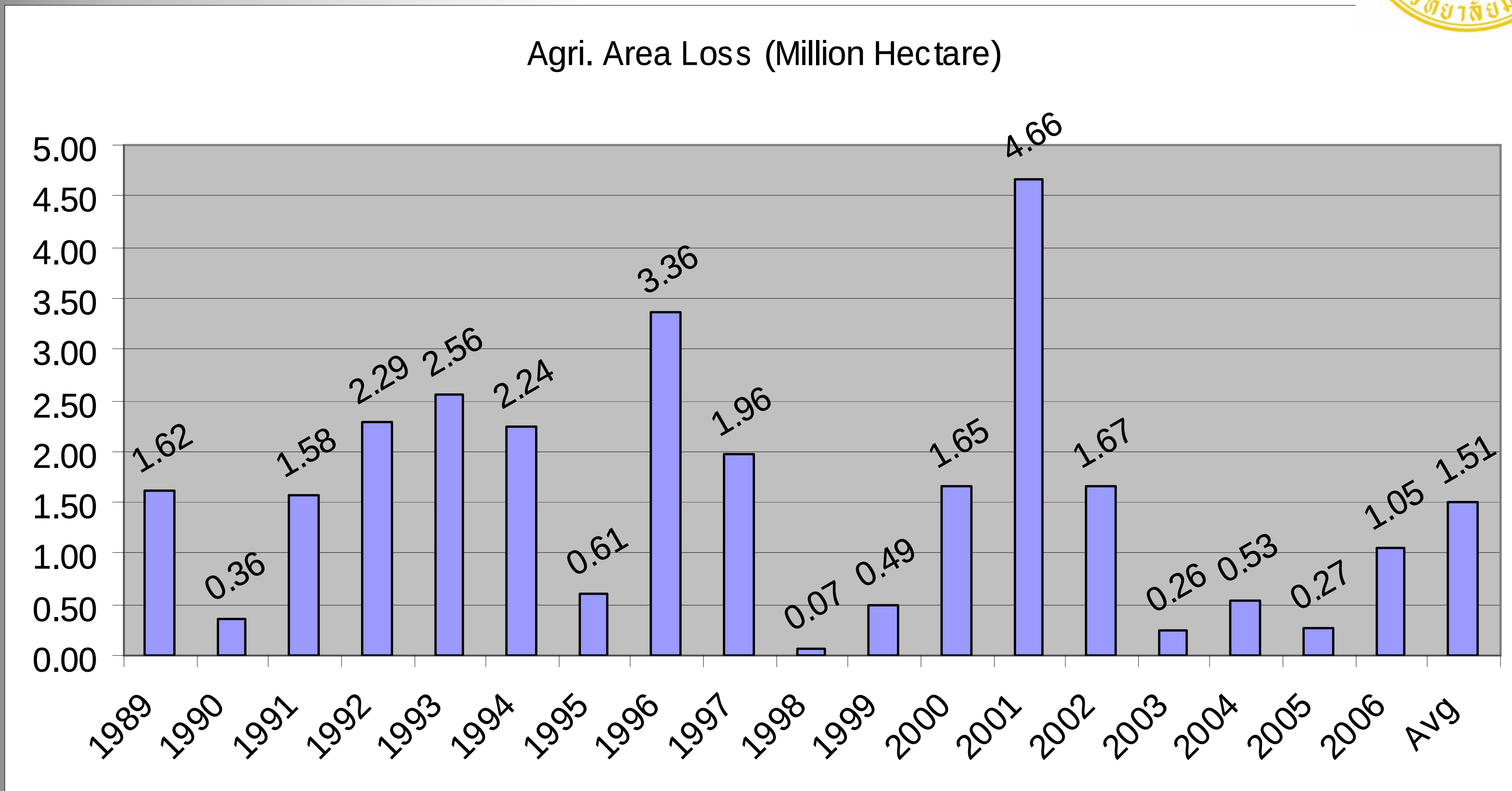
รูปที่ 5-17 แสดงความสัมพันธ์ระหว่าง ความเร็วลม และความสูงคลื่นในช่วงลมมรสุม ตะวันออกเฉียงเหนือและลมมรสุมตะวันตกเฉียงใต้ 20 ปี ระหว่างปี 1987-2007

Trend of Number of Days that Temp. above 33 Celsius in 1976-2006, 2010-2039, 2050-2059, and 2080-2089



Trend of Number of Days that Temp. is below 15 Celsius in 1976-2006, 2010-2039, 2050-2059, and 2080-2089

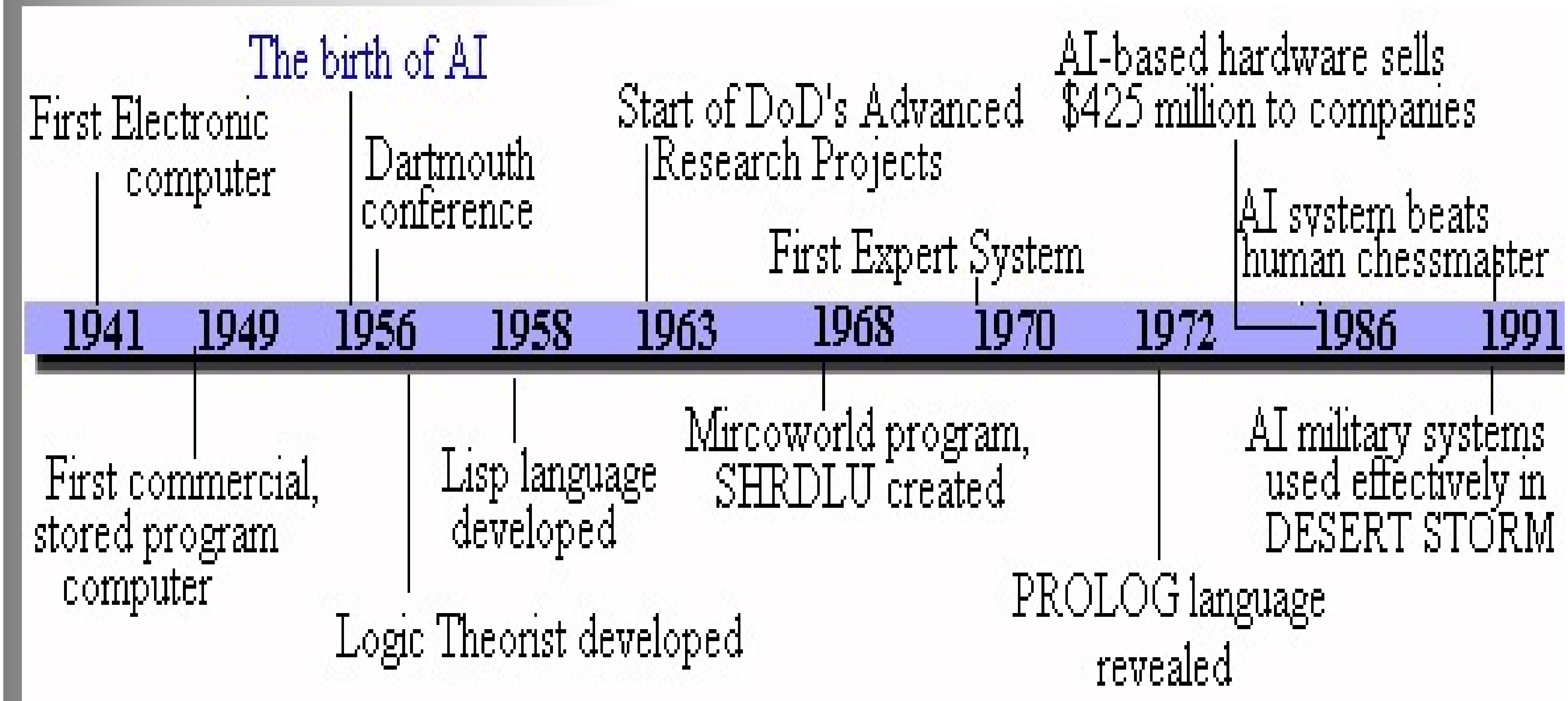



Agri. Area Loss (Million Hectare)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1.62
0.36
1.58
2.29
2.56
2.24
0.61
3.36
1.96
0.07
0.49
1.65
4.66
1.67
0.26
0.53
0.27
1.05
1.51
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Avg

Optimisation Approaches

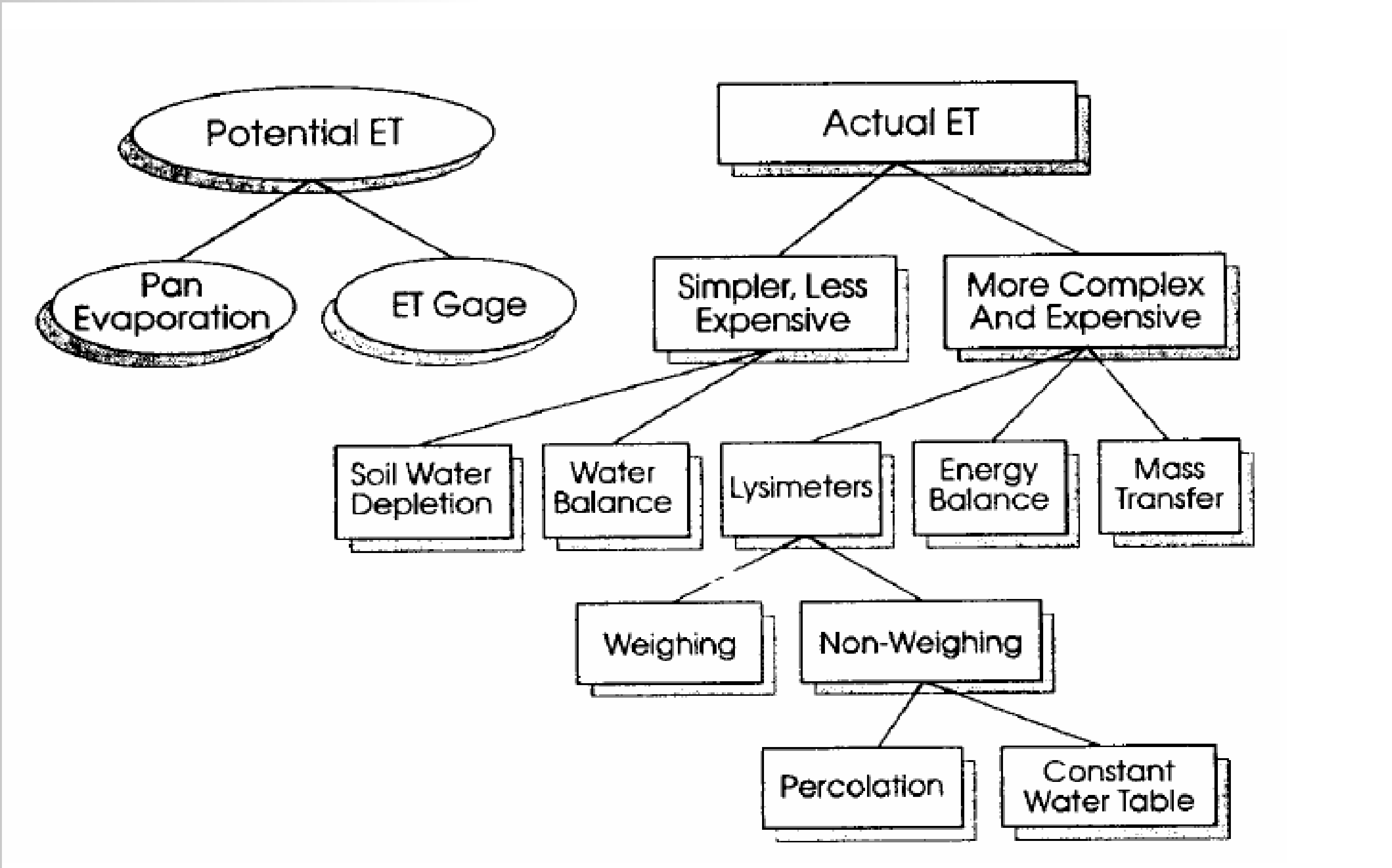
- *linear Programming*
- *dynamic programming (DP)*
- *non-linear programming (quadratic, QP)*
- *simulated annealing (SA)*
- *evolutionary algorithms (genetic algorithms, GAs)*
- *artificial neural networks (ANNs)*

Time Line of Major of AI Events



Modelling 1.
Crop Evapotranspiration under Climate Change

Adaptation to Evapotranspiration Measurement



Source: Ward A.D., E. W. J. (1995). *Environmental Hydrology*. **Boca Raton, FL: CRC Lewis Publishers.**

Modified Penman

$$ET_o = c\,[W.R_n + (1 - W)\,f(u)\,(e_a - e_d)]$$

where:

(ea - ed) = vapour pressure deficit which is the difference between saturation vapour pressure (ea) at T mean in m bar (Table 3.I) and actual vapour pressure (ed) in m bar where ed = ea. RH/100.

f(U) = wind function of f(U) = 0.27 (1 + U/100) with U in Km/day measured at 2 m height

Rn = total net radiation in mm/day or

Rn = 0.75Rs - Rnl

where:

Rs is incoming shortwave radiation in mm/day either measured or obtained from Rs = (0.25 + 0.50 n/N)Ra.

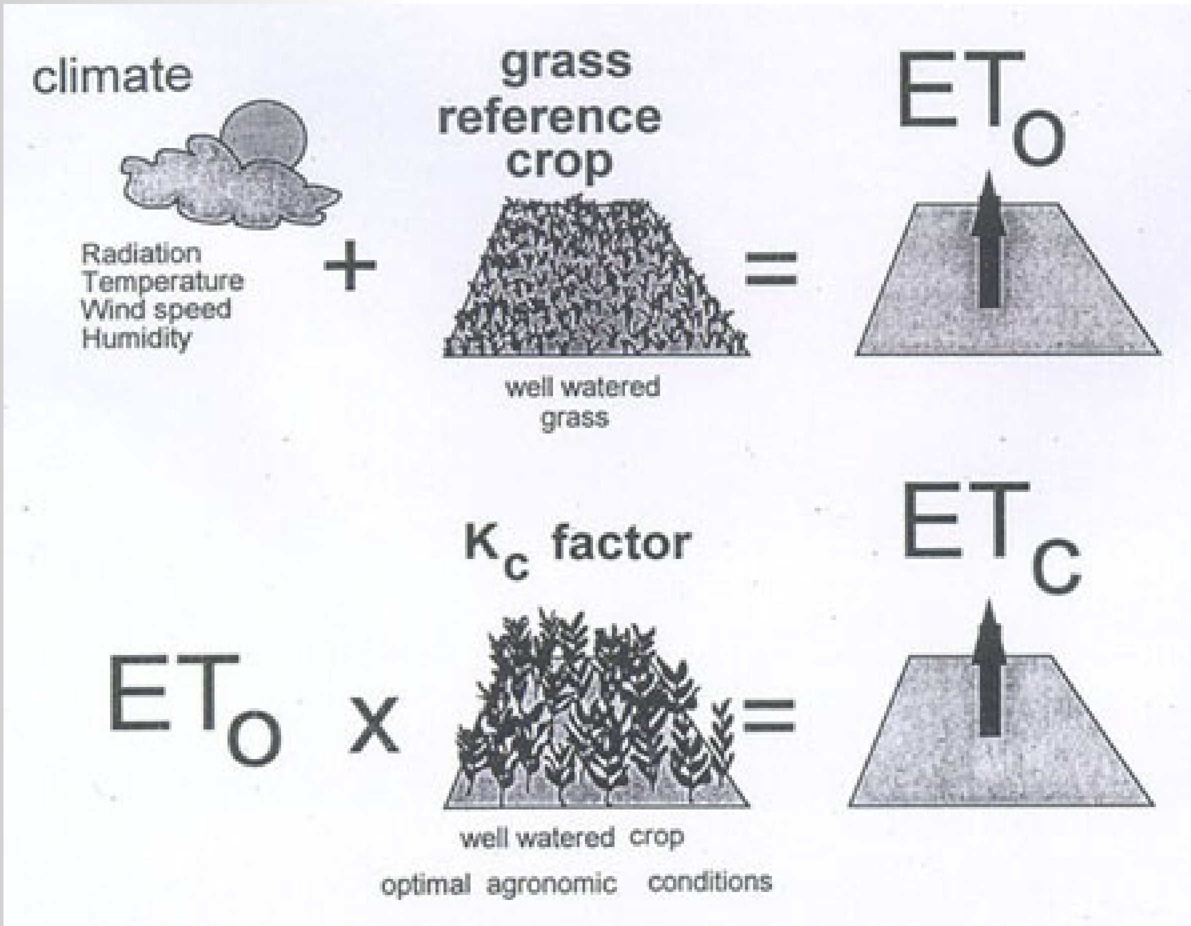
Ra is extra-terrestrial radiation in mm/day,

n is the mean actual sunshine duration in hour/day and N is maximum possible sunshine duration in hour/day

Rnl is net longwave radiation in mm/day and is a function of temperature, f(T), of actual vapour pressure, f(ed) and sunshine duration f(n/N), or Rnl = f(T). f(n/N). f(ed)

W = temperature and altitude dependent weighting factor

c = adjustment factor for ratio U day/U night, for RHmax and for Rs

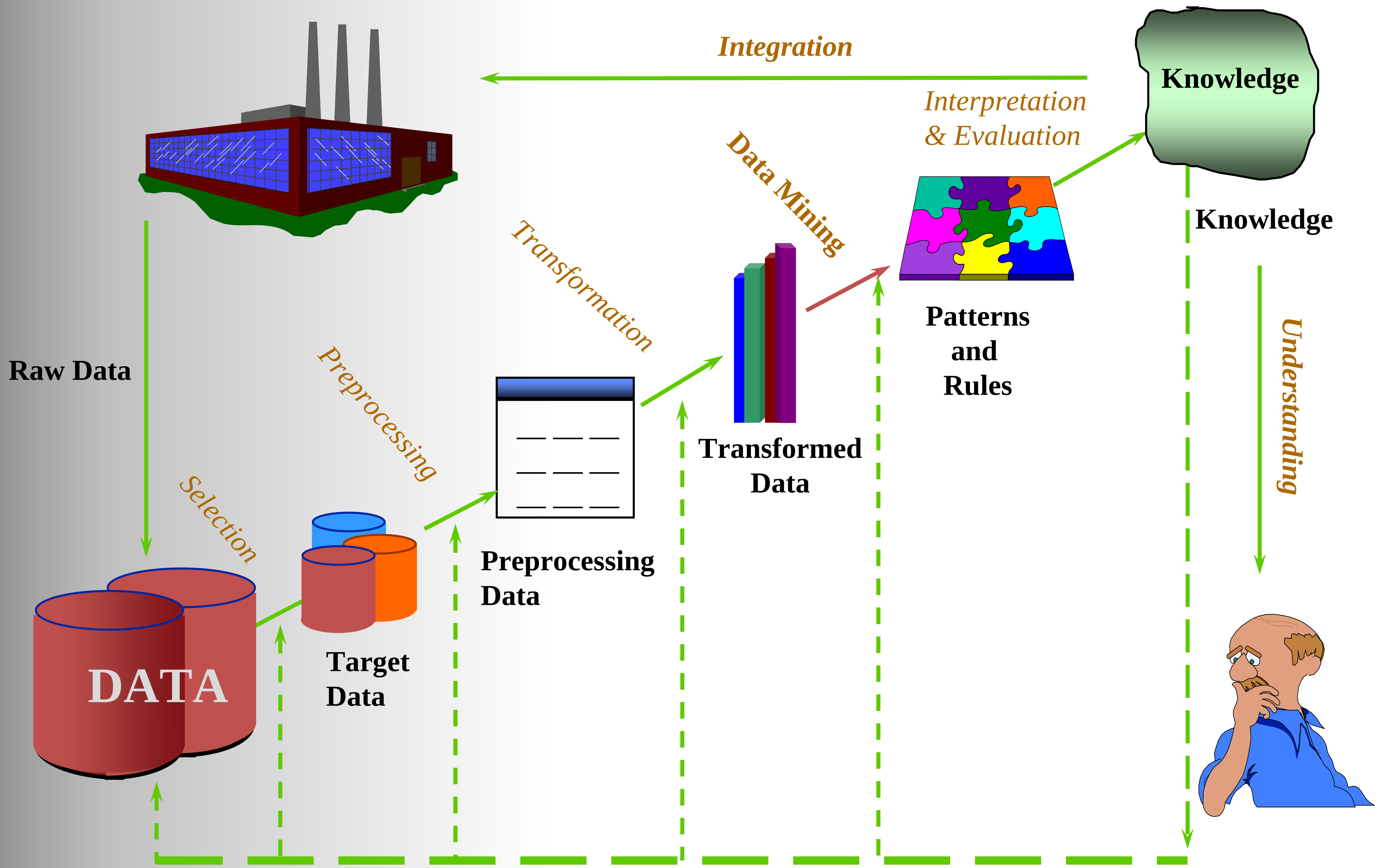


Source: http://www.fao.org/docrep/X0490E/x0490e04.htm

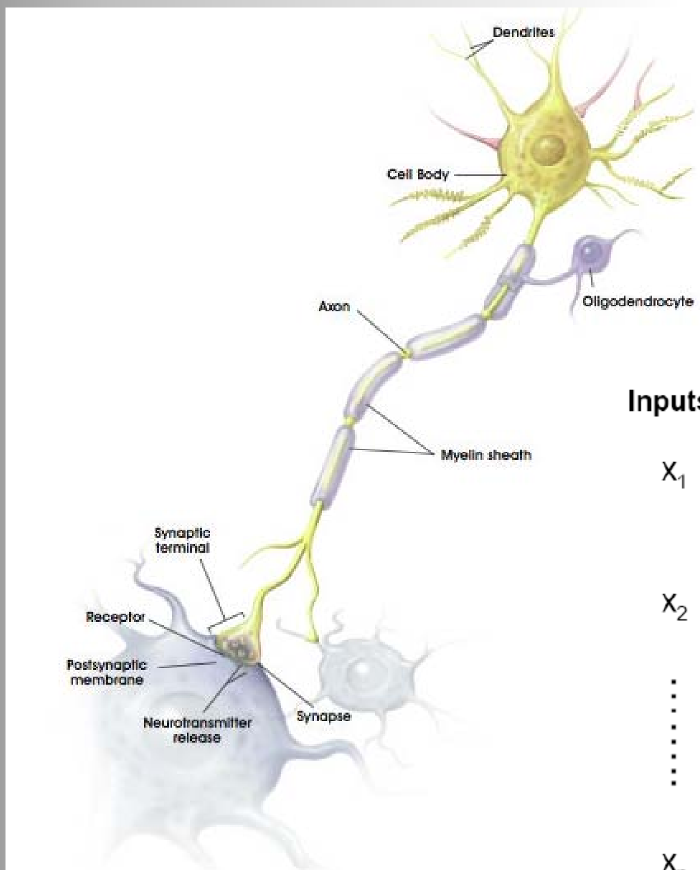
Artificial Neural Networks (ANNS)

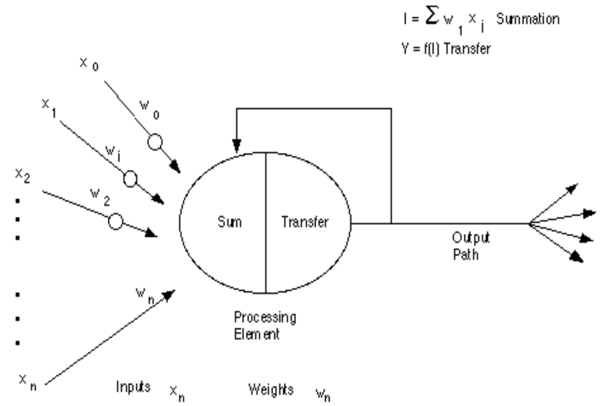
ANNS have evolved from the development of pattern recognition systems from remotely sensed data. They are in effect artificial devices, which can be trained to recognize certain patterns in an input, then respond in a trained manner in producing an output from that input.

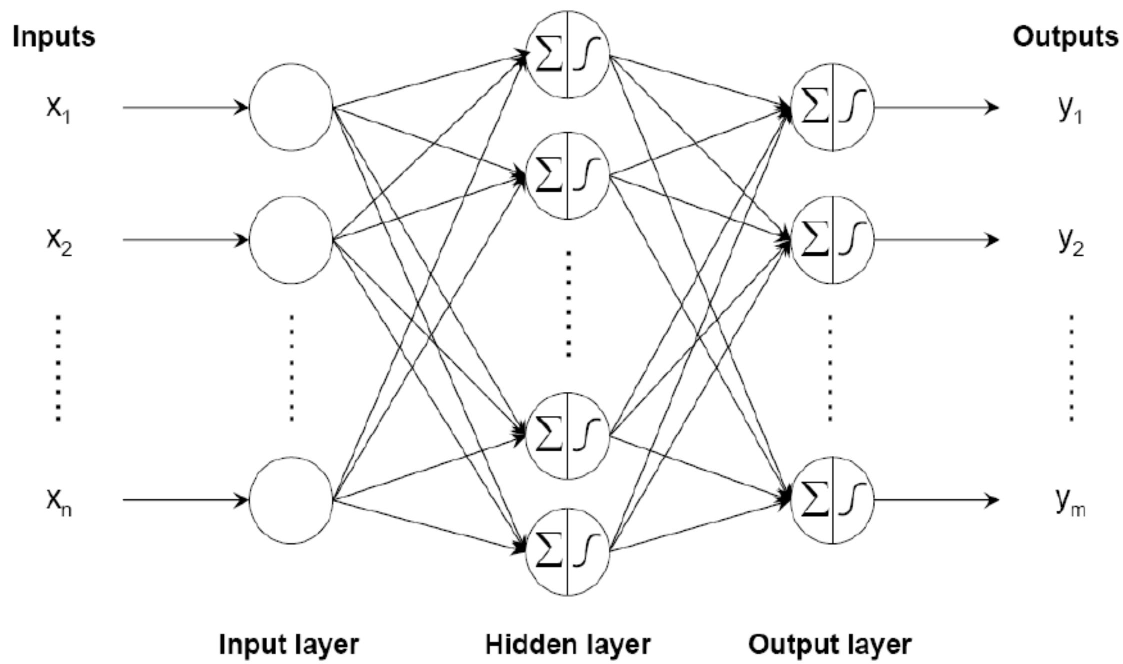
A Study on ETp (or ETo) with Data Mining



Neural Network







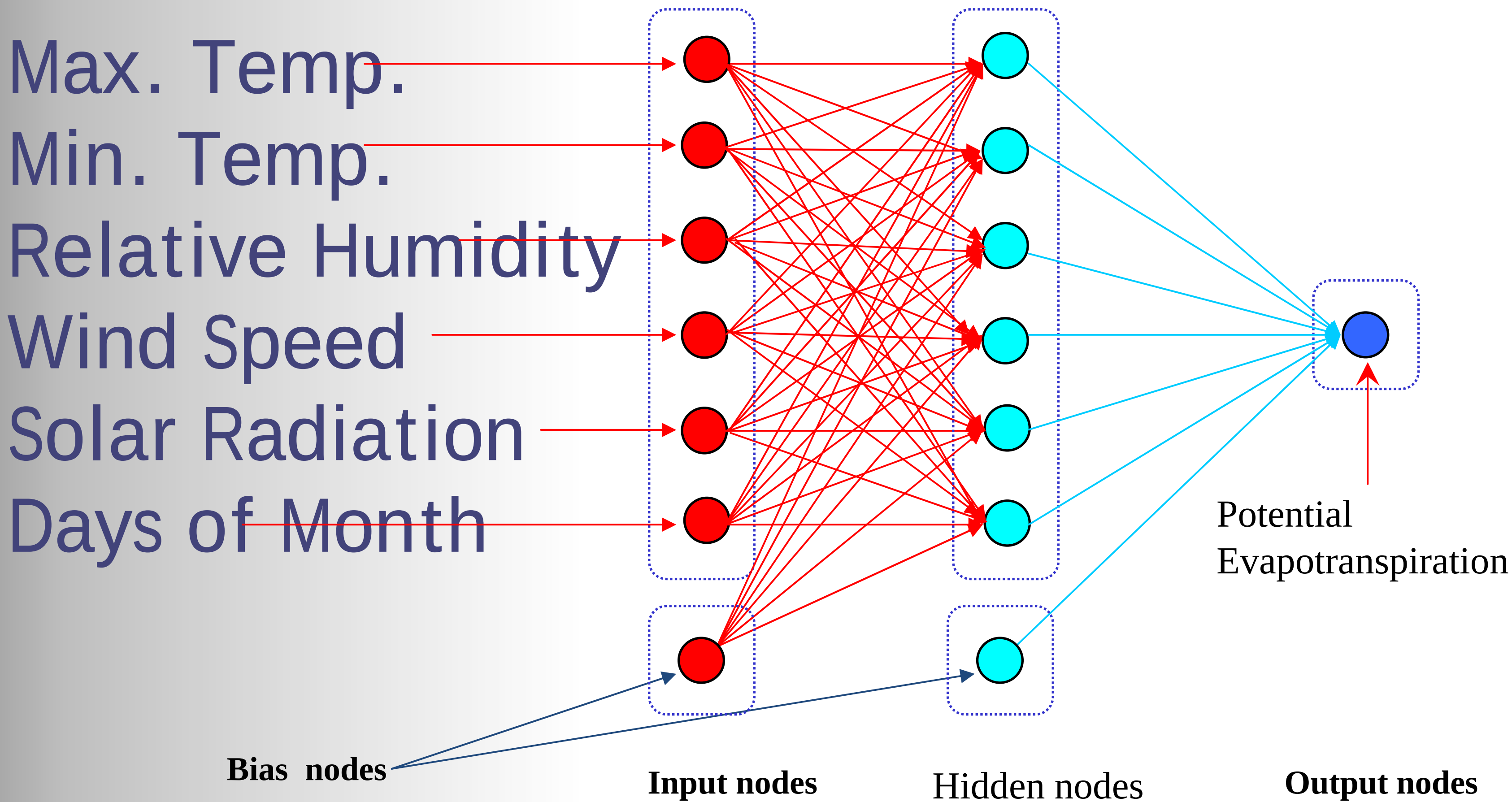
Framework

- Climatic Data Collection
- Create ANNs Model
- Model Verification and Model Testing
- ETo Obtained from Model
- Calculation of ETc

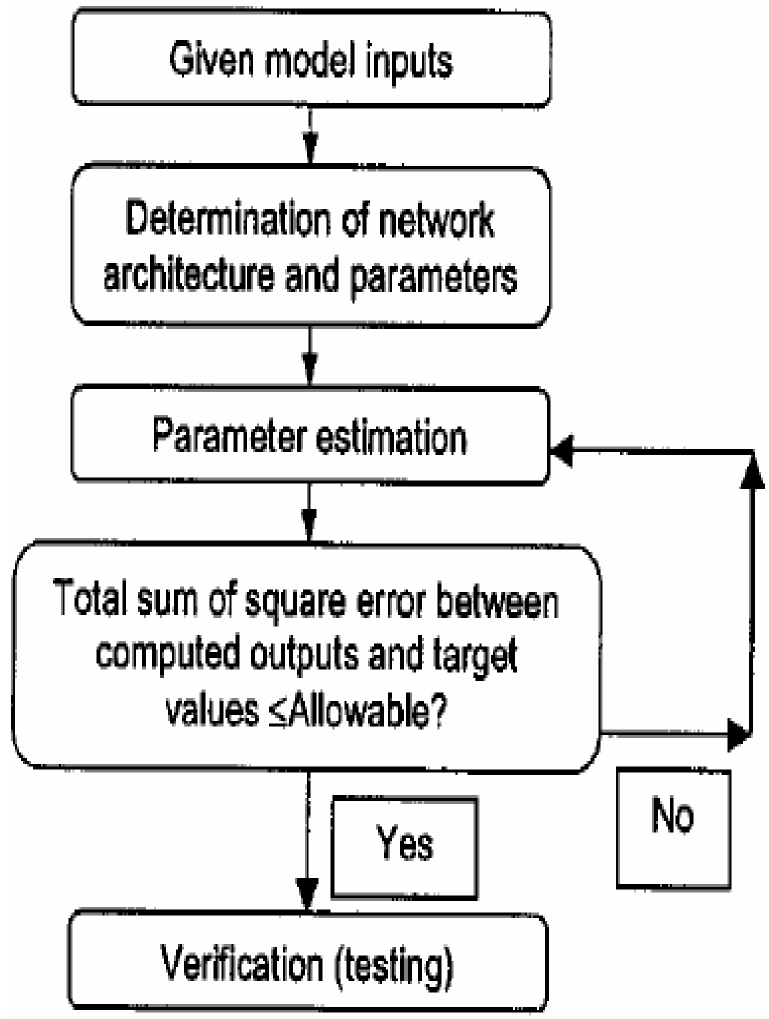
Climatic Data Input

- Climatic Data 1980–1989 with 2,555 input
  - Max. Temp. (Celsius)
  - Min. Temp. (Celsius)
  - Relative Humidity (%)
  - Wind Speed (km/day)
  - Solar Radiation (mm/day)
  - Number of Days in Month (days)
  - Evaporation from Pan (mm)

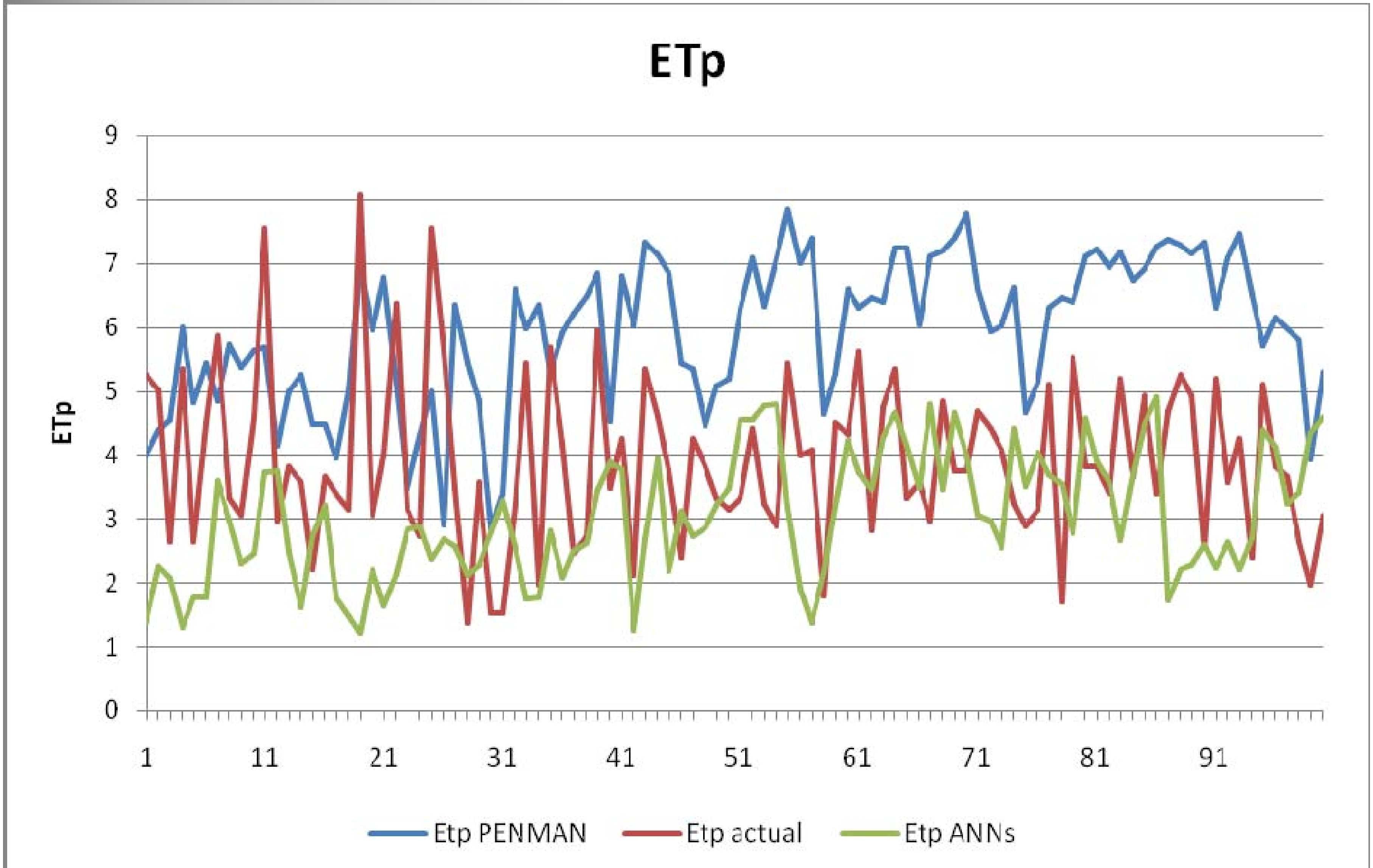
Neural Network Model

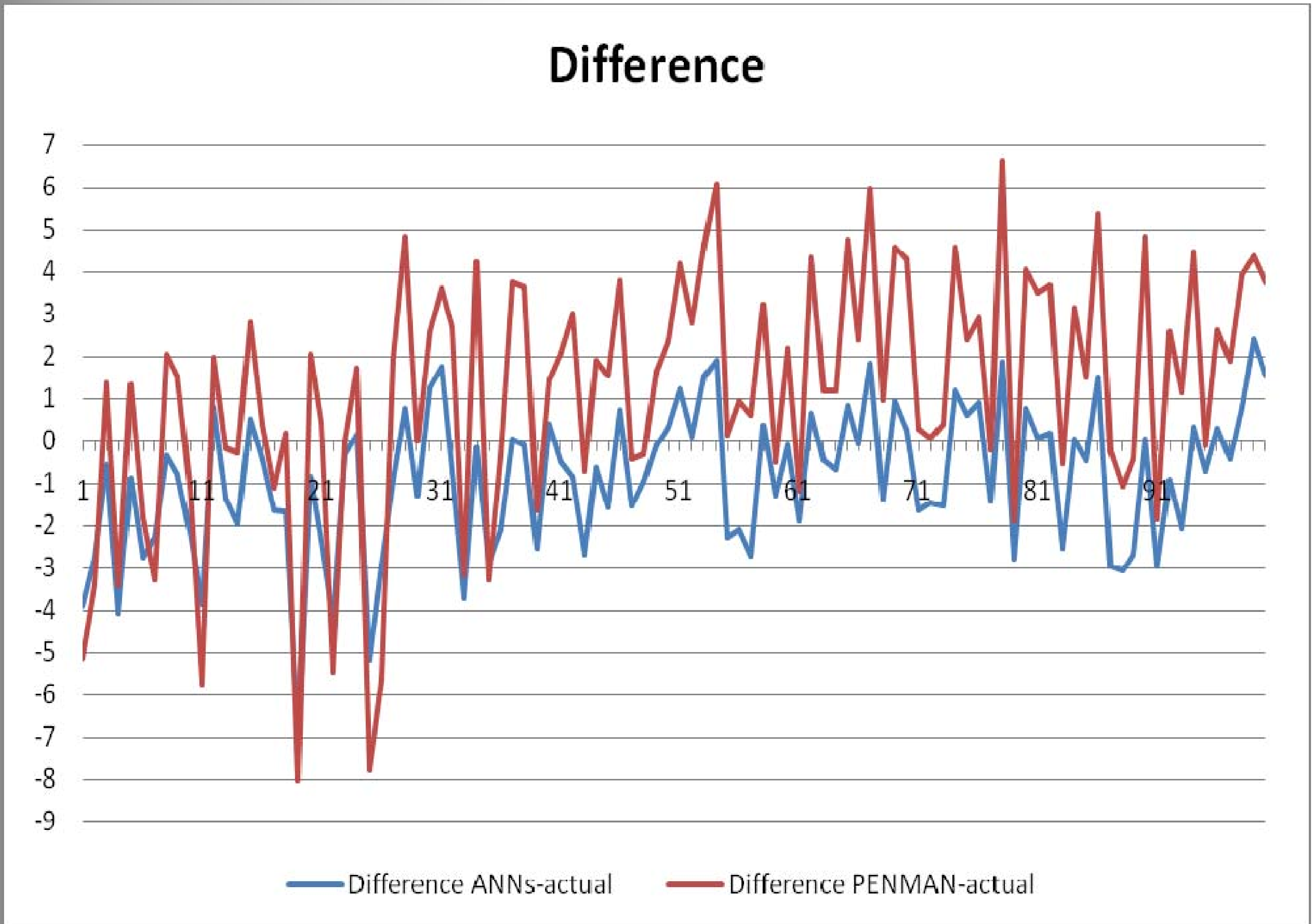


KDD (Knowledge Discovery in Database


Given model inputs
Determination of network architecture and parameters
Parameter estimation
Total sum of square error between computed outputs and target values ≤Allowable?
Yes
No
Verification (testing)

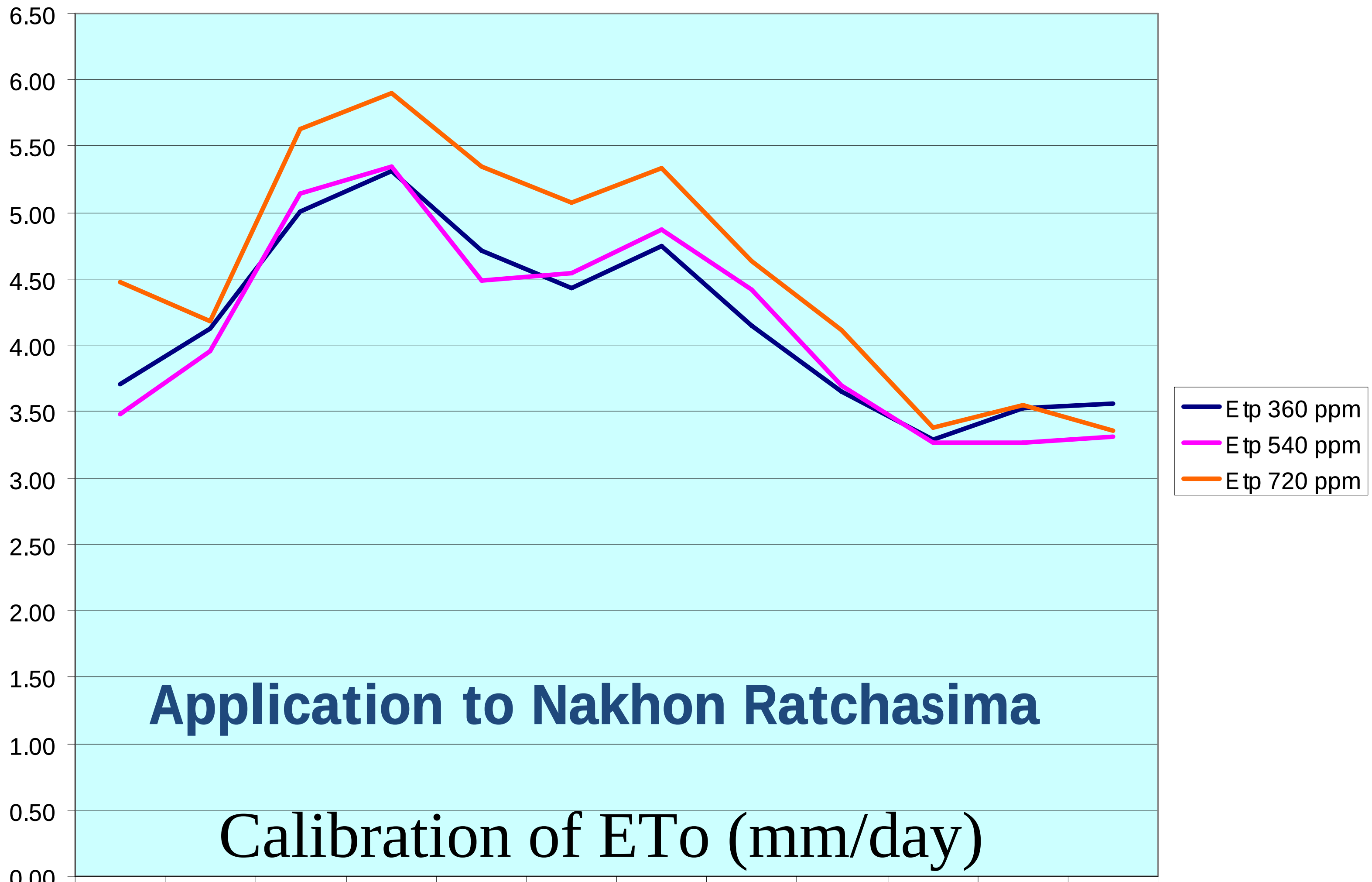
Comparison of ETo Obtained from Modified Penman, ANNs, and Actual Data, Thailand





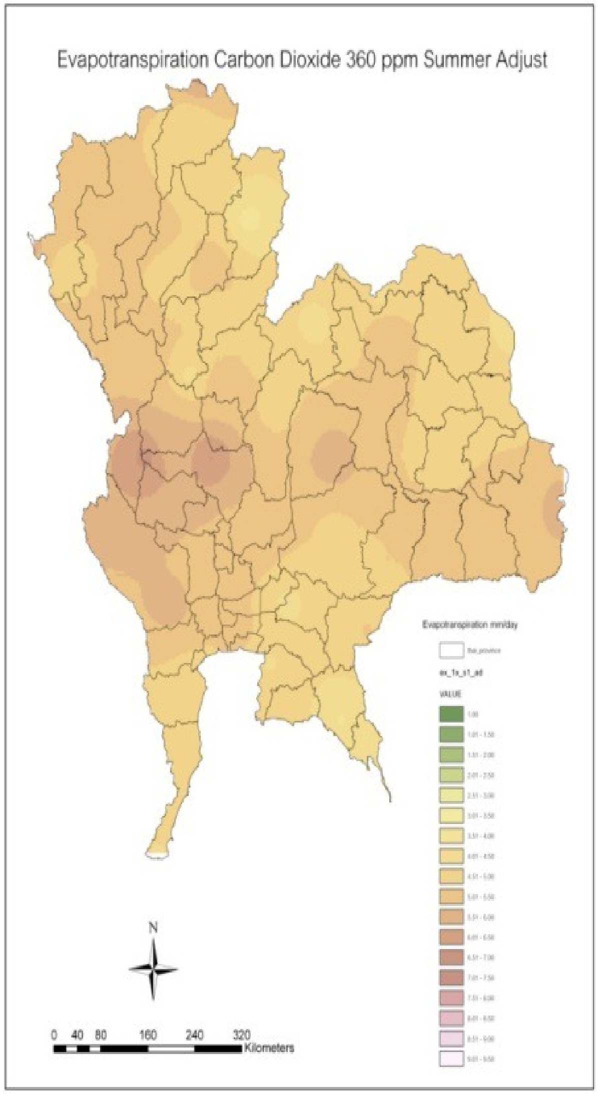
Difference
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
1
11
21
31
41
51
61
71
81
91
Difference ANNs-actual
Difference PENMAN-actual

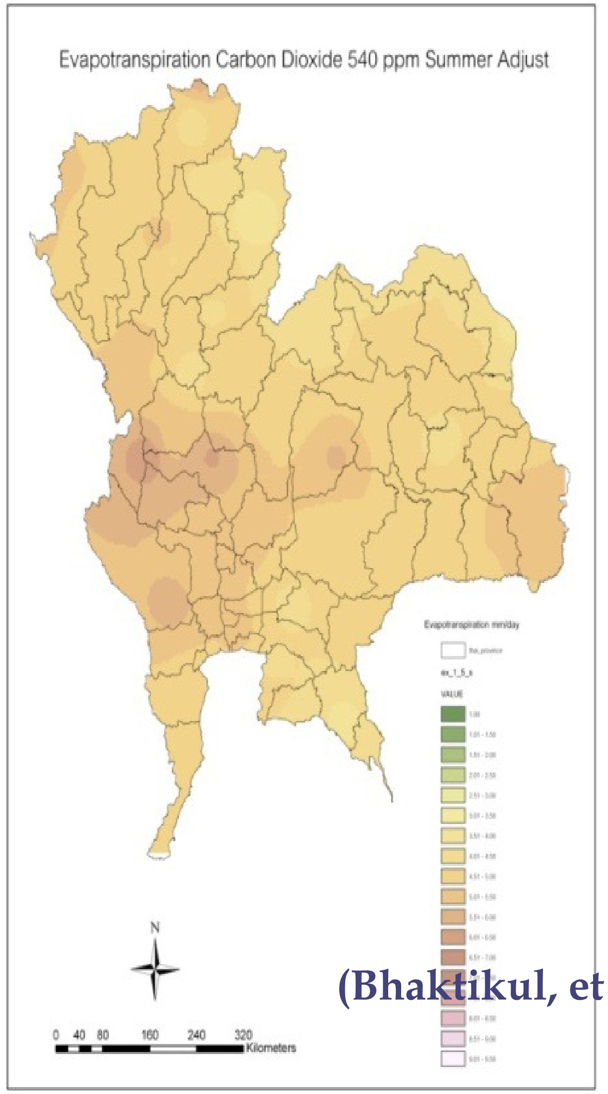
Conditions Input to the Models:
Atmospheric CO_2 = 360 / 540 / 720 ppm

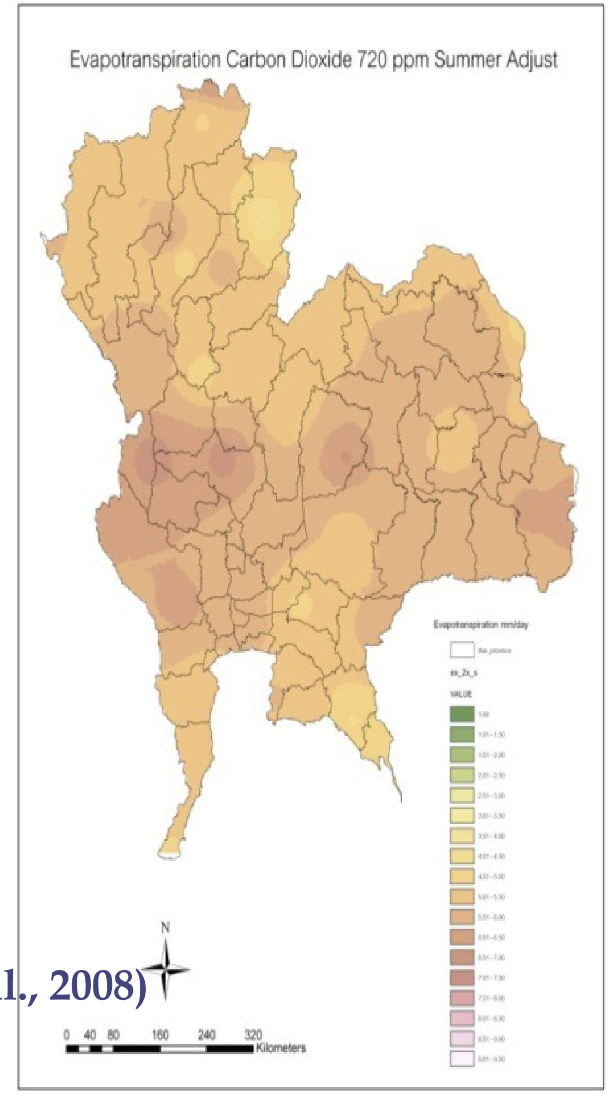


	1	2	3	4	5	6	7	8	9	10	11	12
E tp 360 ppm	3.71	4.12	5.01	5.31	4.71	4.43	4.75	4.14	3.65	3.29	3.52	3.56
E tp 540 ppm	3.48	3.95	5.14	5.35	4.48	4.54	4.88	4.42	3.69	3.27	3.27	3.31
E tp 720 ppm	4.48	4.18	5.63	5.90	5.35	5.08	5.33	4.63	4.12	3.38	3.55	3.36

ETo with CO_2 360 ppm Summer

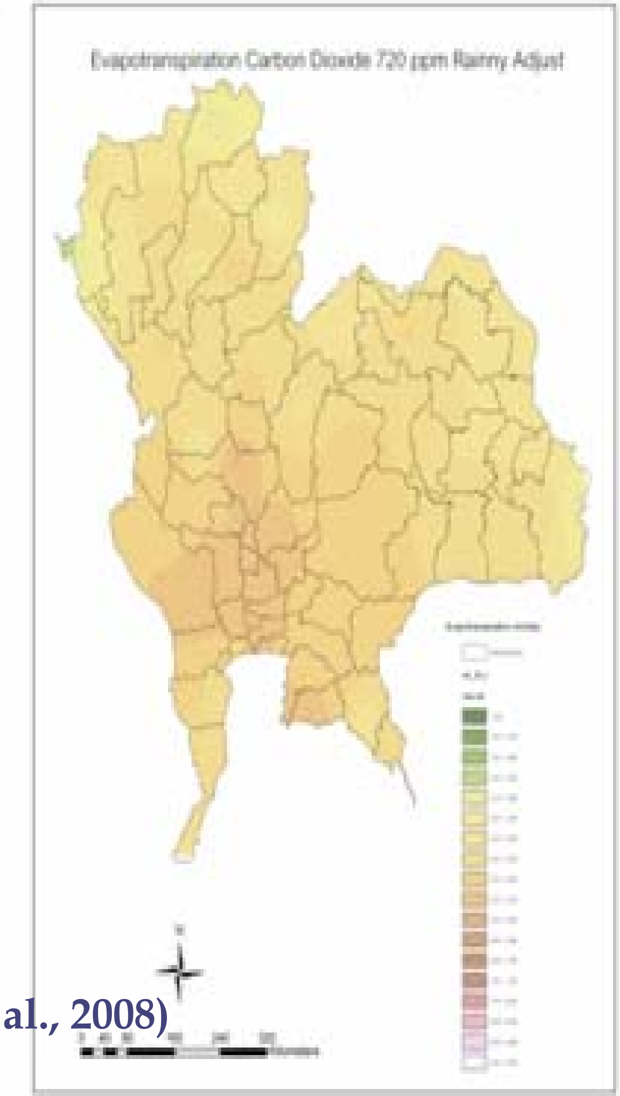






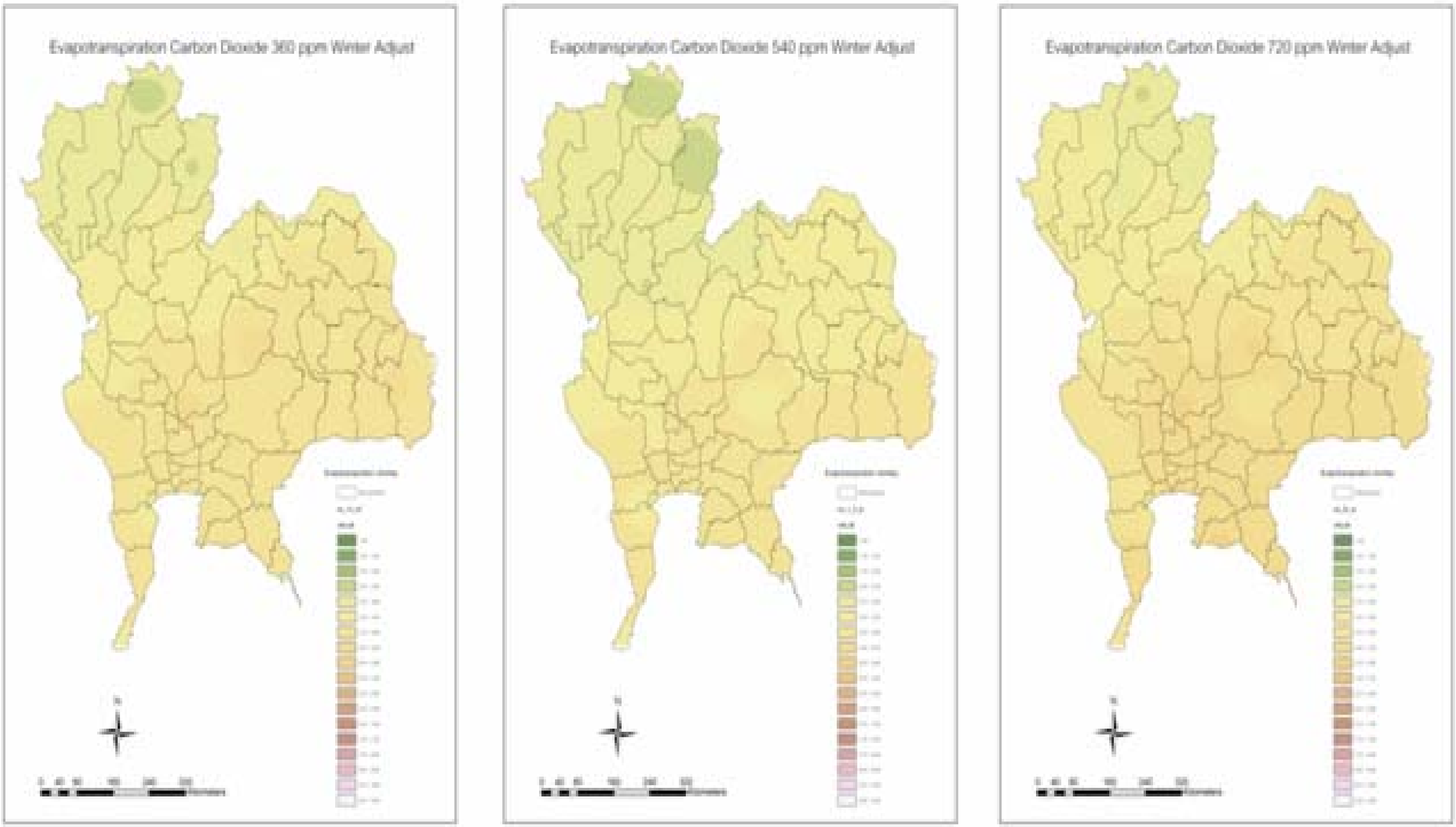
(Bhaktikul, et al., 2008)

ETo with CO_2 360 ppm Rainy



(Bhaktikul, et al., 2008)

ETo with CO_2 360 ppm Winter



(Bhaktikul, et al., 2008)

Publications

- *Bhaktikul, K., Noimunwai, W., Chinvanno, S. 2009. Estimation of Crop Evapotranspiration: Rice, Maize and Sugarcane under Climate Change using Data Mining Technique, Proceedings of 4th THAICID National Symposium (Irrigation and Productivity: Challenge in Food, Energy and Environment, Thailand Commission on Irrigation and Drainage, BKK, pp 133-140.*
- *Noimunwai, W.. Bhaktikul, K. Pumijumnong, N., Nantasenamart, C. and Chinawanno, S. 2008. Estimation of Potential Evapotranspiration (ETo) under Climate Change using Data Mining: Case study of Thailand, Proceeding of Annual Conference of Faculty of Environment and Resource Studies, Mahidol University. 30th 31st Oct.*

Applications

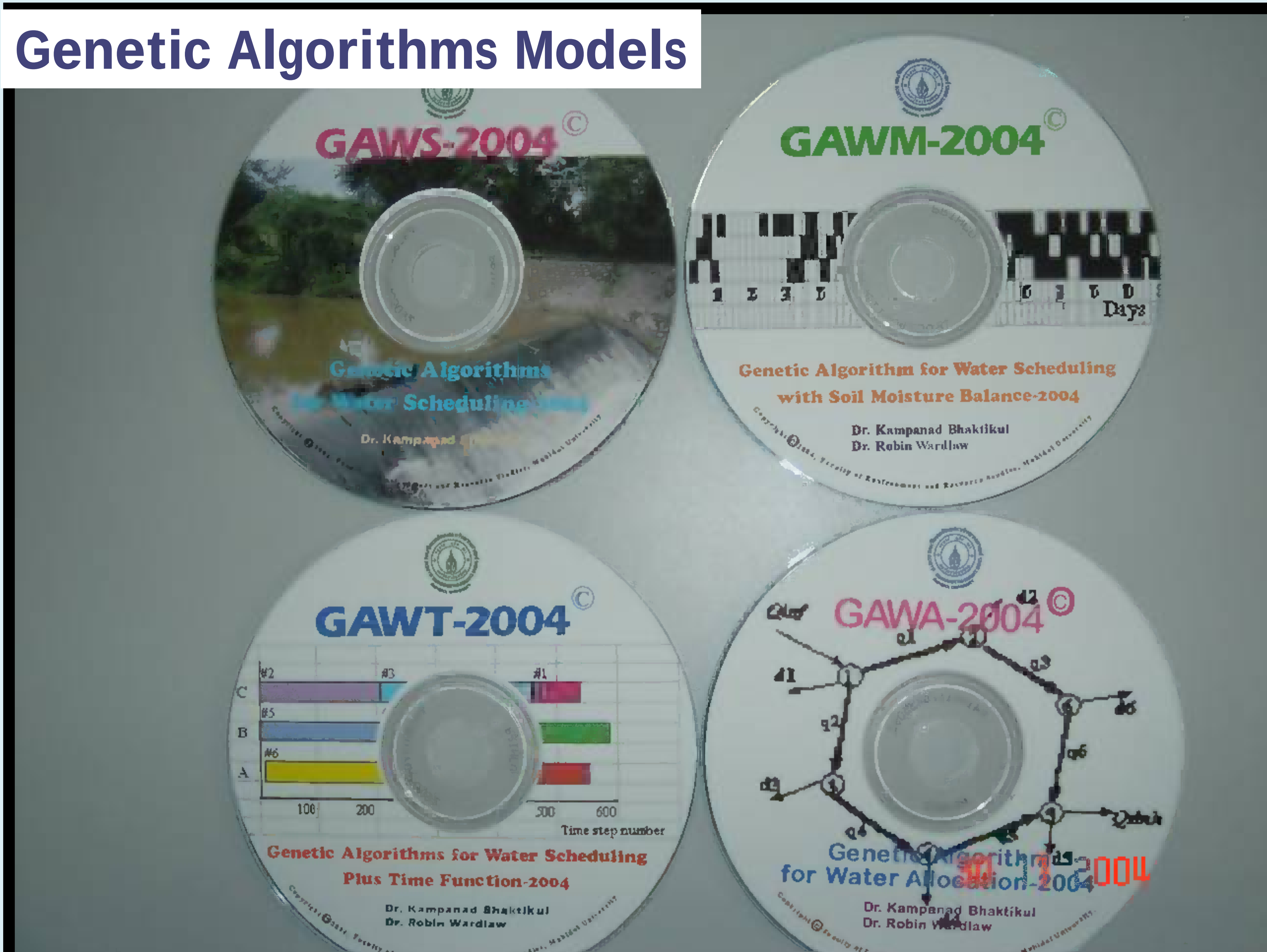
- *There is possibility to make use of the result at RID.*

Further Studies

- *Shifting of crop calendar*
- *Adjustment of reservoir operation study and operational rule curve*
- *Irrigation water requirement*
- *Water management*
- *Preparation for real time water allocation in the time of flood and drought- extreme cases*

Modelling 2.
Real Time Equitable Water Allocation under Floods and Droughts

Genetic Algorithms Models



Genetic Algorithms

The GA is search algorithm based upon the mechanics of natural selection, derived from the theory of natural evolution (evolutionary algorithm).

GA simulates mechanisms of population genetics and natural rules of survival in pursuit of ideas of adaptation.

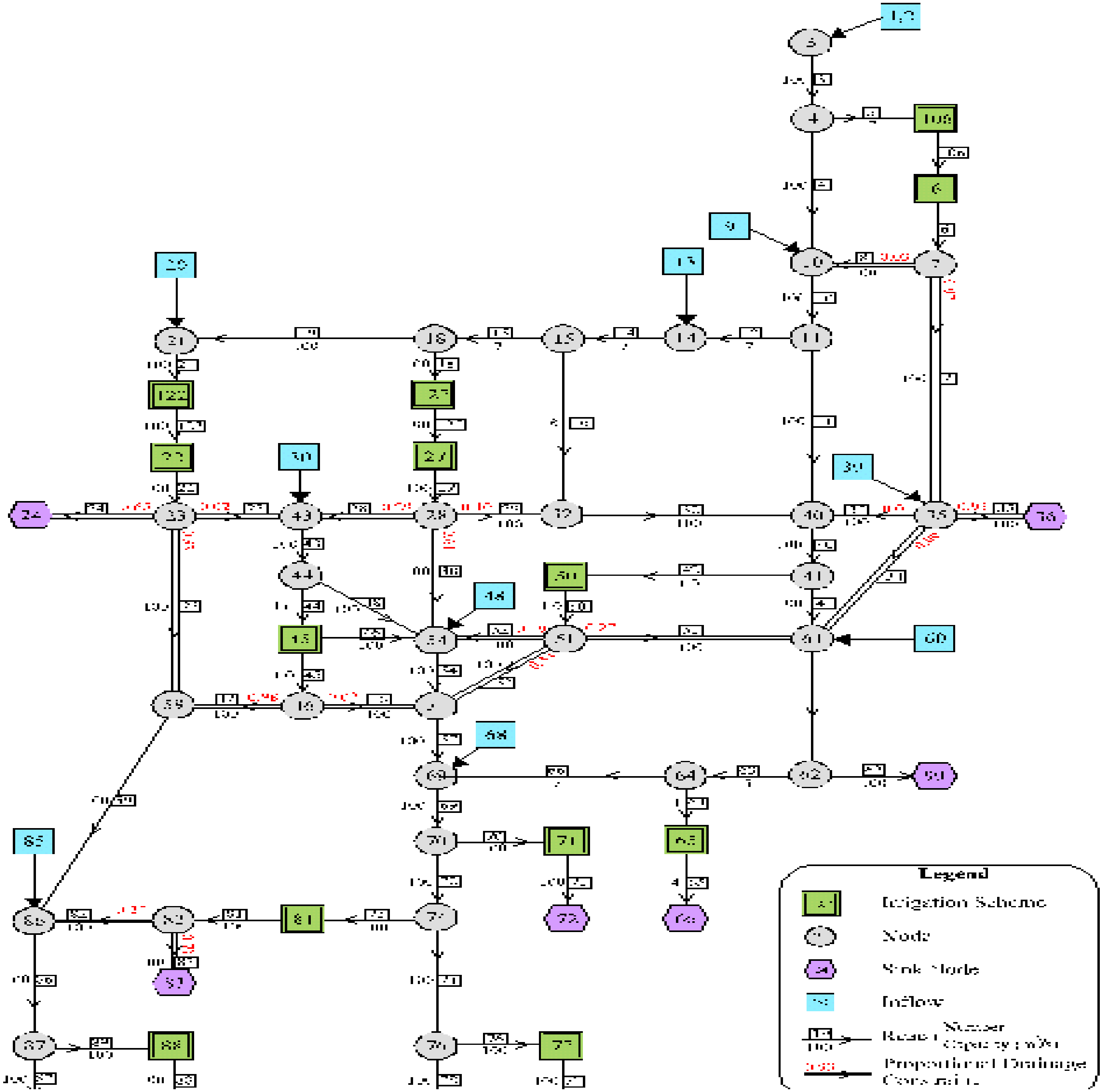
Activities, Studies, and Research related to CC

Development of Technology to use in real time equitable water allocation in flood and drought extreme cases;

- Root zone soil moisture balance
- Water scheduling in complex system
- Equitable water allocation

Comparison of Natural and GA

chromosome	string
gene	feature, character
allele	feature value
locus	string position
genotype	structure
phenotype	alternative solution
epistasis	nonlinearity


Legend
Irrigation Scheme
Node
Sink Node
Inflow

The Water Allocation Problem

- **To ensure the equitable distribution of water supplies within an irrigation system.**

- **It is not a planning problem in the crops are assumed to be in the ground.**

- **It is not a scheduling problem in that irrigation supplies are assumed to be run of river.**

Why GA？

- GA is flexible and easily set up for
a wide range of linear and non-linear objective functions.

GA is an alternative approach.

How the GAs work?

- work with a coding of parameter set
- search from a population of points
- use objective function information
- use probabilistic transition rules,

Goldberg (1989).

Three Operators of Genetic Algorithm

Selection Operator

- string are selected for inclusion in the reproduction process

Crossover Operator

- permits the exchange of genes between pairs of chromosomes in a population

Mutation Operator

- permits new genetic material to be introduced to a population

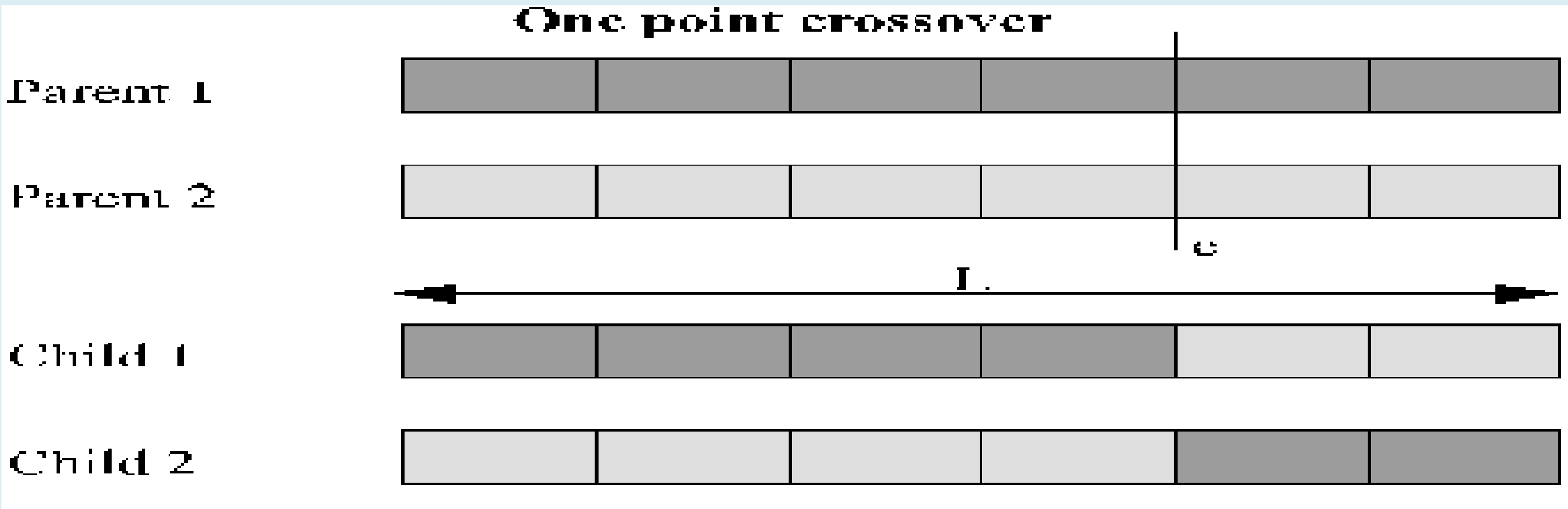
Probability of Selection (P_i)

$$P_i = \frac{f_i}{\sum_{i=1}^{n} f_i}$$

f_i = fitness of individual chromosome in that generation

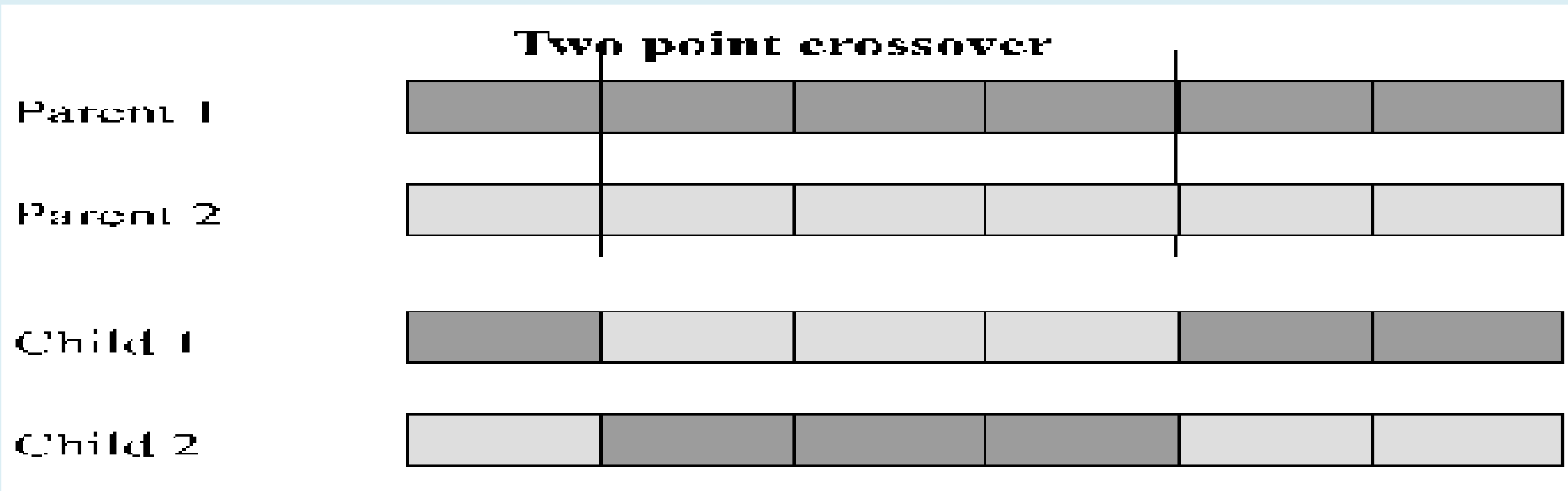
n = population size

One Point Crossover

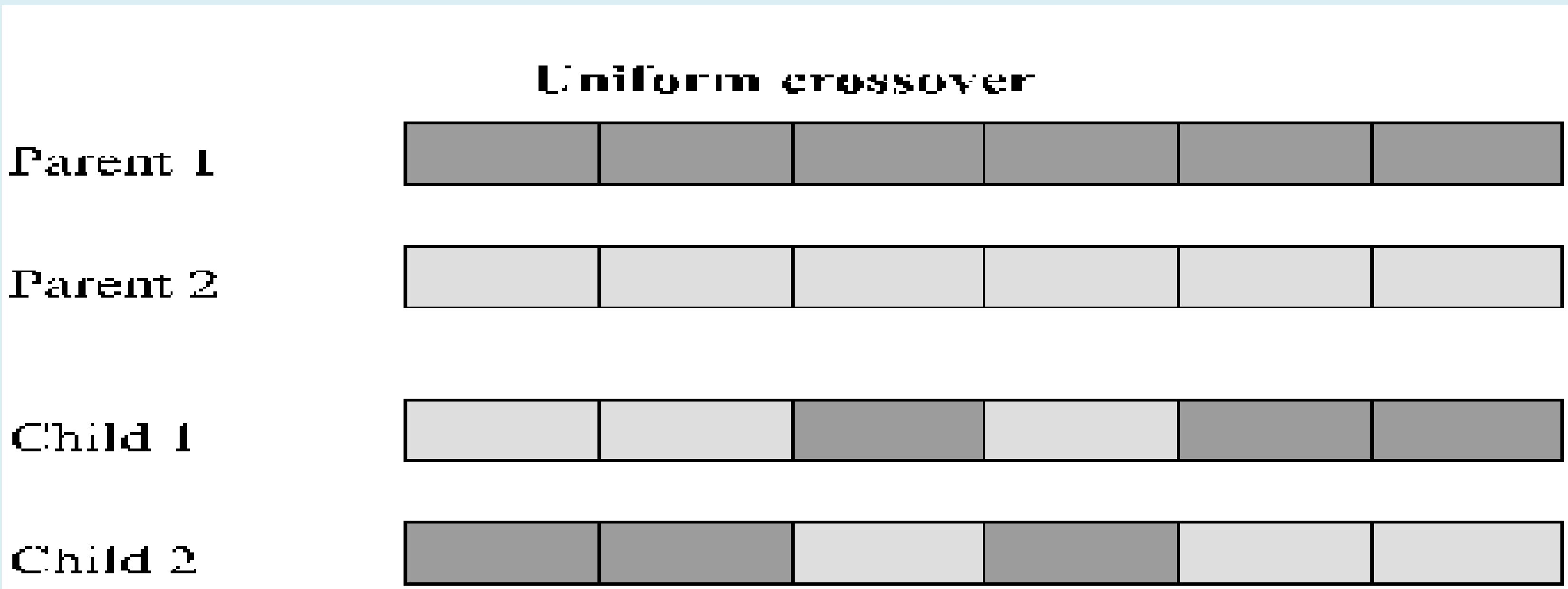


Approaches to crossover (after Wardlaw and Sharif, 1999)

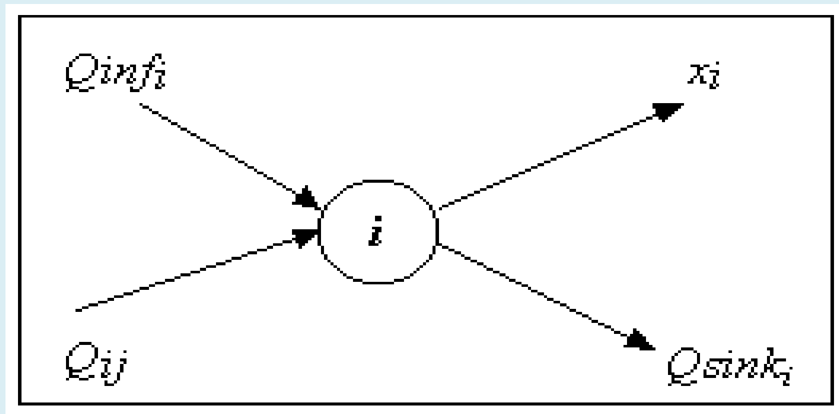
Two Point Crossover



Uniform Crossover



Nodal Water Balance



Objective Function

$$\text{Minimise } Z = \sum_{i=1}^{n} \frac{(d_i - x_i)^2}{d_i}$$

Constraints

- i) Capacity constraint: $Q_{ij} <= qmax_{ij}$
- ii) nodal balance constraint:

$$Qinf_i + \sum_{j=1}^{m} Q_{ij} - x_i - Qsink_i = 0$$

- iii) supply constraint: $x_i <= d_i$

Penalty Function 1

i) If $Q_{ij} > qmax_{ij}$

$$P_1 = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{|Q_{ij} - qmax_{ij}|}{qmax_{ij}}$$

Penalty Function 2

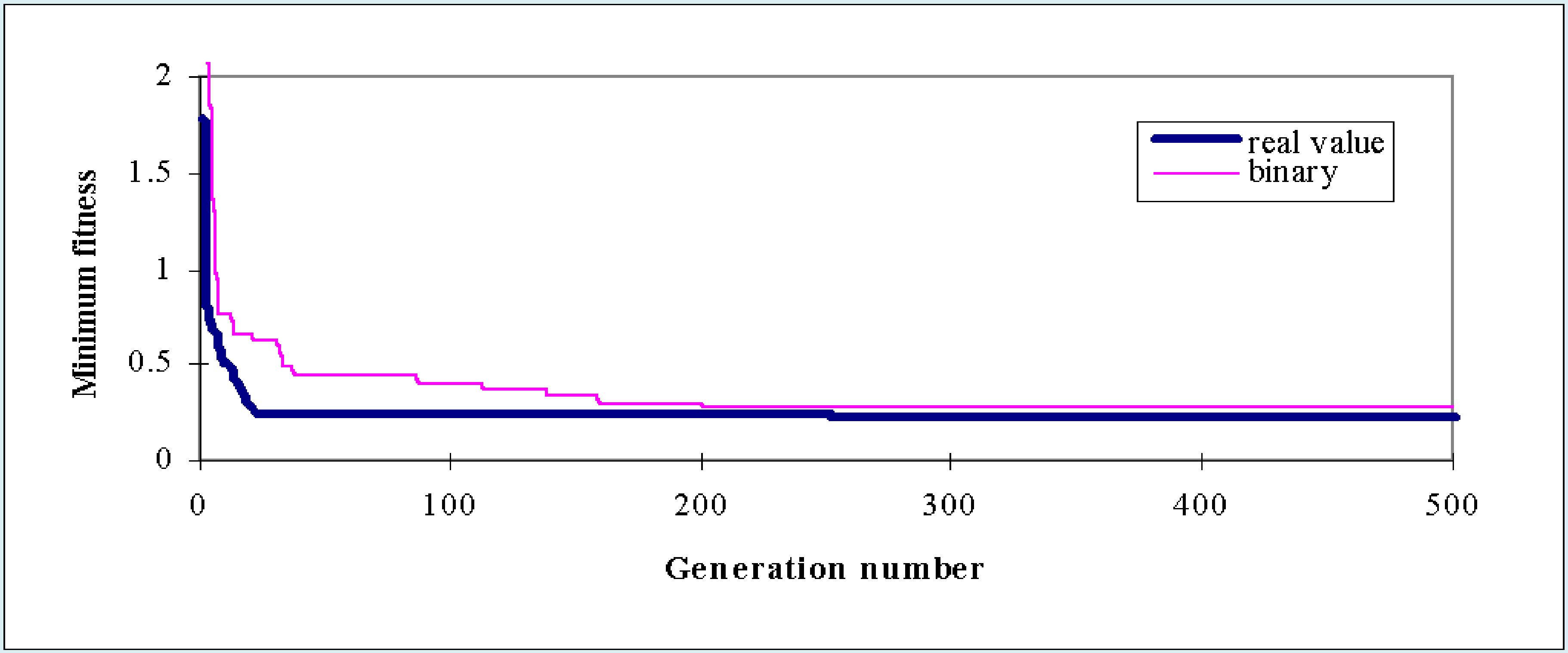
ii) *If nodal balance > 0.001*

$$P_2 = \sum_{i=1}^{n} \frac{\left| Qinf_i + \sum_{j=1}^{m} Q_{ij} - x_i - Qsink_i \right|}{Qinf_i + \sum_{j=1}^{r} Q_{ij(in)}}$$

Penalty Function 3

iii) $\quad If\ x_i > d_i \quad P_3 = \sum_{i=1}^{n} \frac{|x_i - d_i|}{d_i}$

Comparison of Solution Progress



Water Balance Penalty Function for Bali System

$$P_3 = \sum_{i=1}^{n} \frac{\left| Qinf_i + \sum_{j=1}^{m} Q_{ij} - x_i - Qsink_i \right|^2}{Qinf_i + \sum_{j=1}^{r} Q_{ij(in)}}$$

Conclusions

- The advantage of GA is that it could solve the problem with any type of objective function and could be easily set up.
- In water allocation problem the appropriate decision variables are the flows that vary as max. and min.capacity of the canals.
- GA has been improved to water allocation problem if the violation of nodal balance constraints decreased.
- GA is able to solve the water allocation problem, reach the optimum and achieves near equity.

Publications

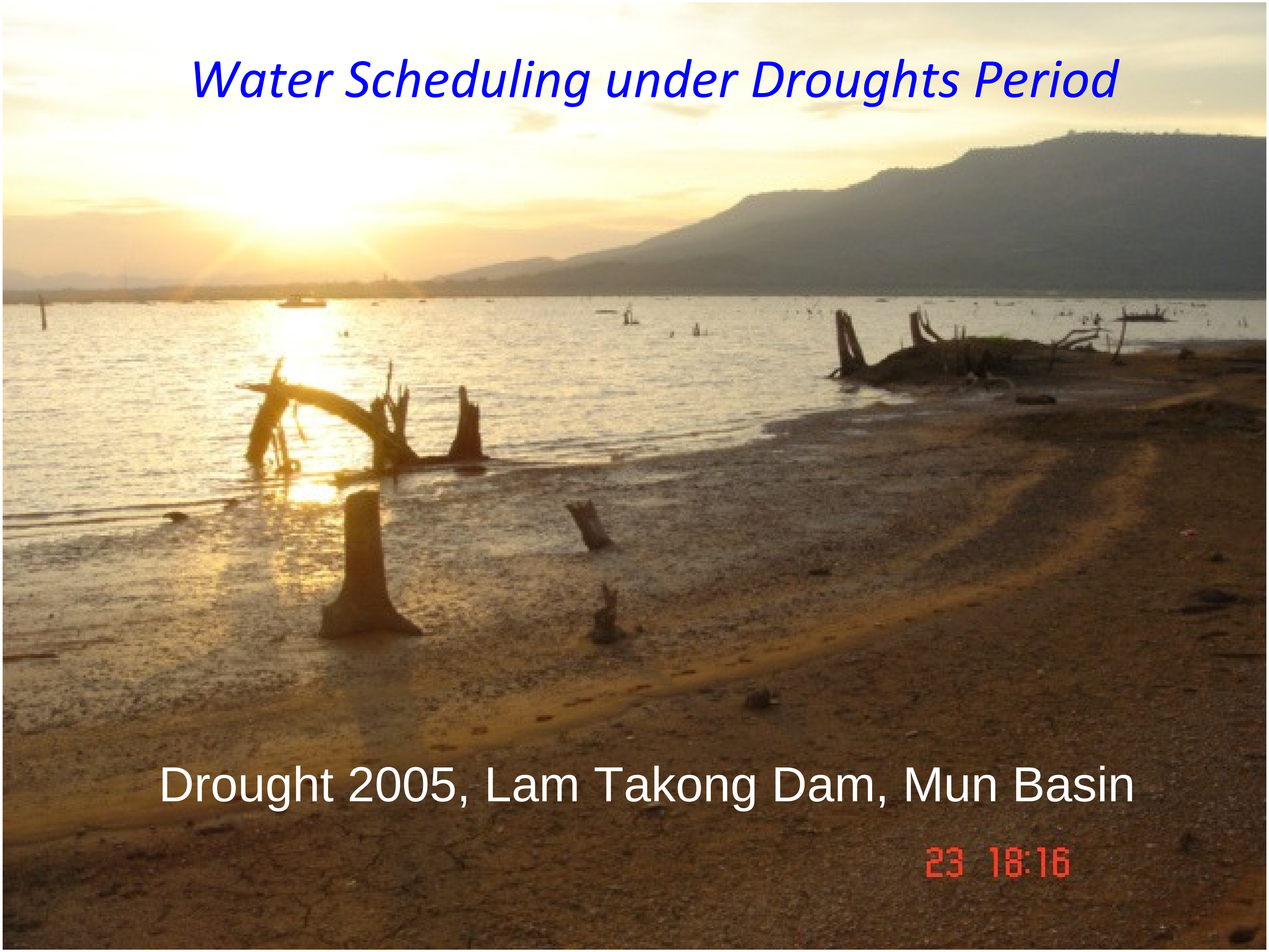
- *Wardlaw, R.W., and Bhaktikul, K. 2001. "Application of a Genetic Algorithm for water allocation problem in an irrigation system", J. of Irrigation and Drainage Engineering, 50(2)159-170.. John Wiley & Sons. ISSN 1531-0353. http://www3.interscience.wiley.com*

Applications

- *Bhaktikul, K., Soiprasert, S., and Sombunying, W. 2007. "Comparison of Genetic Algorithm and WASAM model for Real Time Water Allocation: A case study of Song Phi Nong Irrigation Project". International Network for Water and Ecosystem in Paddy Fields INWEPF 4th Steering Meeting and Symposium: July 5-7, 2007 The Emerald Hotel BKK, Thailand.*

Modelling 3.
Real Time Water Scheduling under Drought Period

Water Scheduling under Droughts Period



Drought 2005, Lam Takong Dam, Mun Basin

A Lateral Canal Scheduling Problem

- **In general water scheduling problem considered was controlled by root zone soil moisture and calculation of irrigation requirements was implicit.**

- **In this application water requirements are to be known. The objective is to determine the timing of allocations to schemes that maximise water use efficiency.**

Secondary Number (1)	Capacity m^3/s (2)	Operation Time (h) (3)	Volume per canal (m^3) (4)	Time block required (5)	Pre-specified starting time period (6)	Result of Optimal starting time period (7)
1	0.4	50	72000	4	1 to 5	1
2	0.8	72	207360	6	1 to 5	1
3	0.4	49	70560	4	1 to 5	1
4	0.5	46	82800	4	1 to 5	1
5	0.8	74	213120	6	1 to 5	1
6	0.4	40	57600	3	1 to 5	1
7	1.0	85	306000	7	1 to 5	1
8	0.6	41	88560	3	1 to 5	1
9	0.4	32	46080	3	1 to 5	1
10	0.5	39	70200	3	1 to 5	1
11	0.6	67	144720	6	3 to 7	3

Objective function used

Minimise Z = $$\sum_{i=0}^{n}\left(Q_i - \sum_{j=1}^{m}(q_{ij}.IFLAG_{ij})\right)^2$$

where: Q_i **= supply canal capacity (m³/s)**

q_{ij} **= capacity of lateral j (m³/s)**

$IFLAG_{ij}$ **= indicator for lateral operation**

m **= number of laterals**

n **= number of time steps in the rotation**

i **= time step**

The Value of *IFLAG*

IFLAG $= 0$

If $i \geq ISTRT_j$ and $i < (ISTRT_j + OT_j)$

IFLAG $= 1$

OT_j **= the operating time for lateral j**

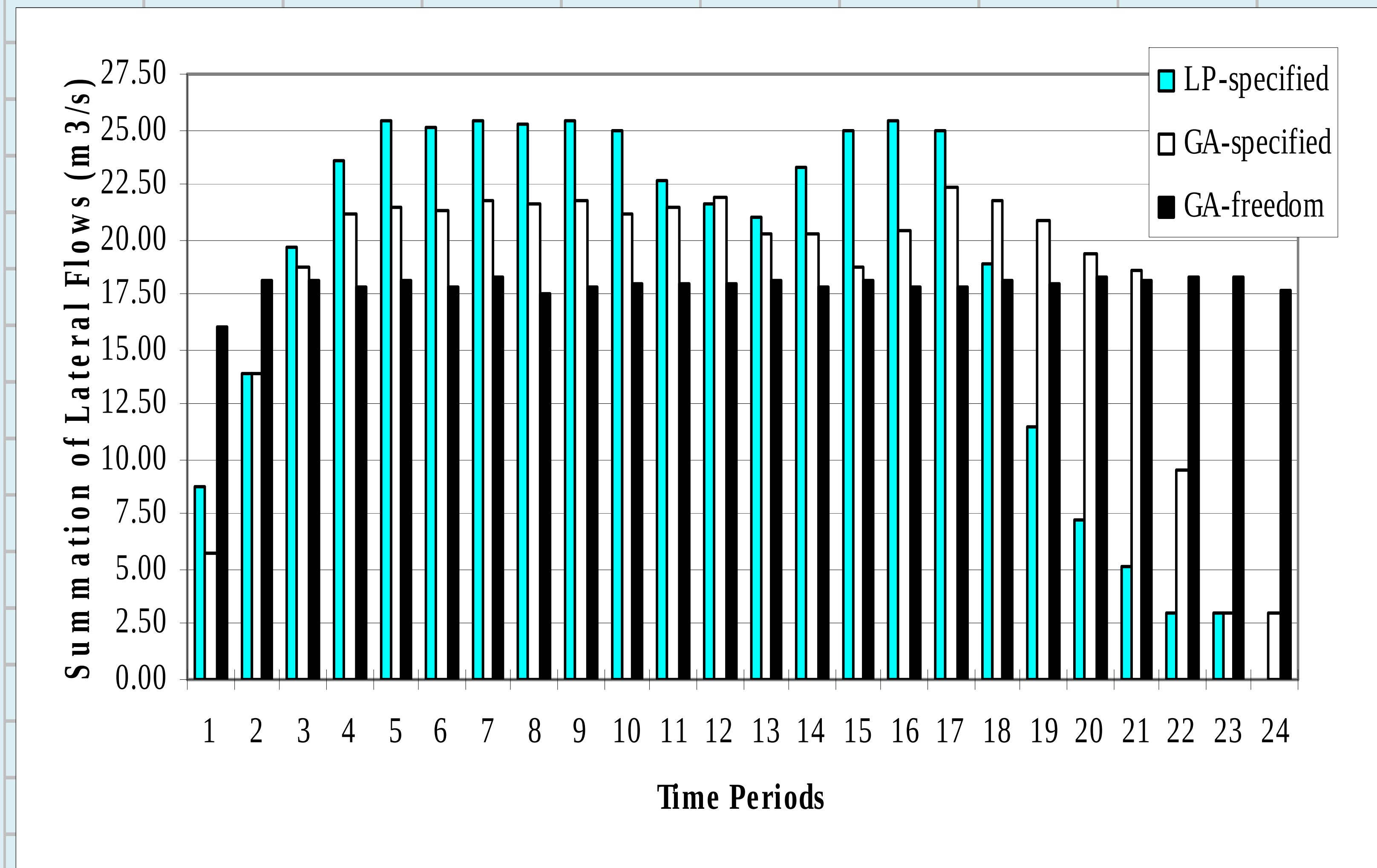
$ISTRT_j$ **= starting time step of operating time**

Constraint

$$If \sum_{j=1}^{m} q_{ij} > Q_i$$

$$P_1 = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} q_{ij} - Q_i \right)$$

Comparison on summation of lateral flows in each time period



Publications

- *Wardlaw, R.W., and Bhaktikul, K. 2004. "Comparison of Genetic Algorithm and Linear Programming Approaches for Lateral Canal Scheduling", J. Irrigation and Drainage Engineering, American Society of Civil Engineers (ASCE). 130(4)311-317. http://scitation.aip.org/iro/*

Applications

- *Thanit, T., and Bhaktikul, K. 2009. An Application of Genetic Algorithm for Pipe System Water Allocation at Raok Reservoir in Rayong Province. Proceedings of 4th THAICID National Symposium, Irrigation and Productivity: Challenge in Food, Energy and Environment, Thailand National Commission on Irrigation and Drainage, BKK, pp 16-32.*
- *Kijpayung, A. Wudhiwanit, W. Bhaktikul, K. 2009. Application of Genetic Algorithms for Determining the Optimal Pipe Size, Engineering Journal, Kasetsart University, BKK, pp 66-2 to 66-12.*

Conclusions

- GA is particularly well suited to this problem. GA is robust and reaches the optimum very quickly.
- GA performs significantly better than the 0-1 LP, which was unable to satisfy the supply canal capacity constraint.
- GA produces a number of candidate solutions and can be used to determine an optimal starting period for each lateral or to determine the optimum starting period within a pre-specified range.

Modelling 4.
Real Time Water Scheduling in Root Zone under Severe Stress

Water Scheduling Problem

The objective in scheduling may be considered to be one of optimising water resources utilisation by maintaining soil moisture between field capacity and wilting point, minimising drainage losses.

Water Scheduling Problem

Thus periods of excess water when soil moisture exceeds field capacity are to be minimised, while maintaining soil moisture above wilting point.

Soil Moisture Balance

For the purposes of this research, a relatively simple soil moisture balance model has been developed, based on field capacity and wilting point.

Soil Moisture Balance

In any soil layer, moisture content is not permitted to exceed field capacity - any water application in excess of field capacity is assumed to drain to the next soil layer.

Soil Moisture Balance

When soil moisture is between field capacity and wilting point, drainage does not occur, and water is removed from the soil only by evapotranspiration.

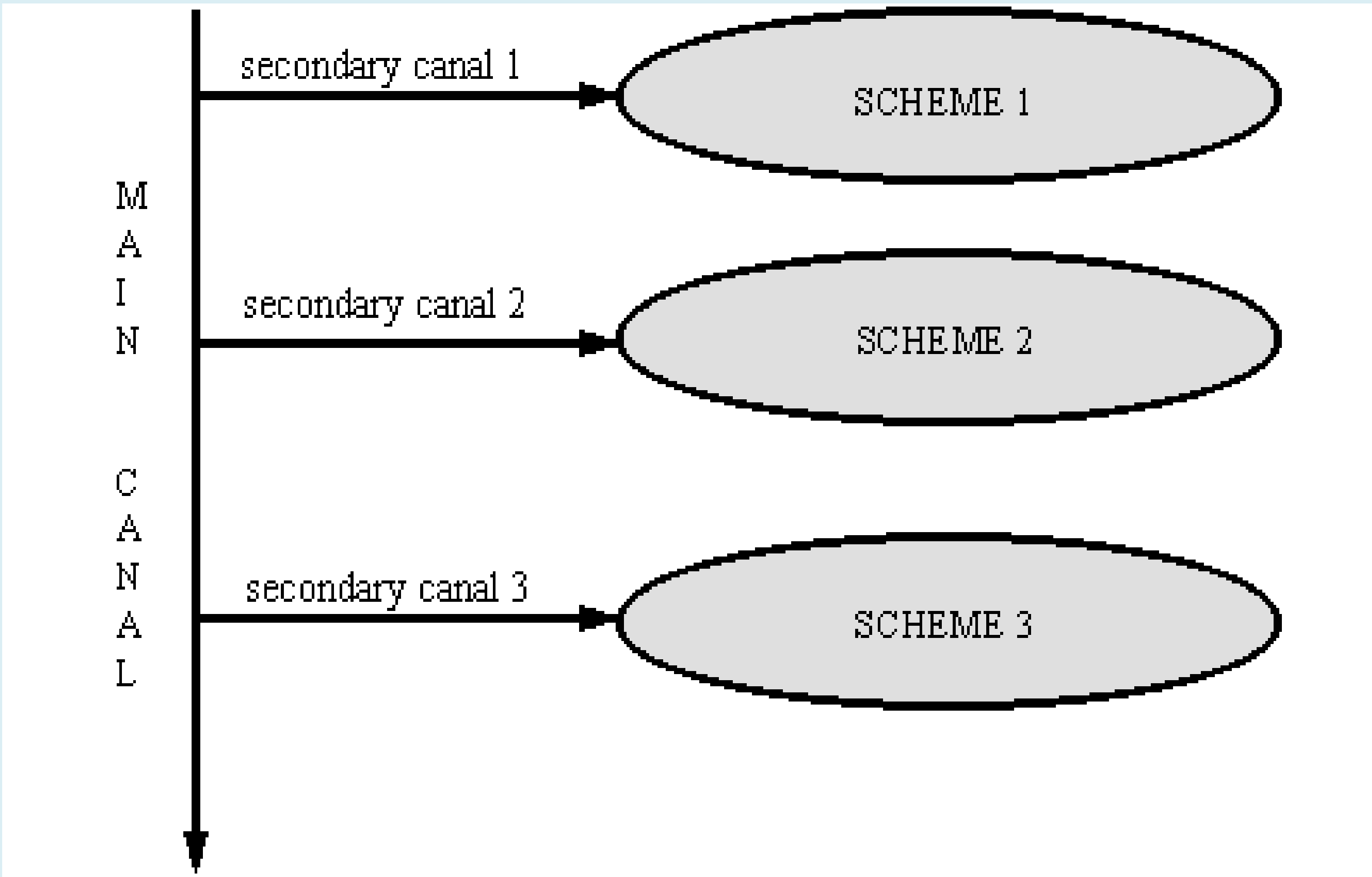
Soil Moisture Balance

Wilting point is defined by an allowable depletion factor, which is crop dependent, and is the point at which soil moisture stress starts to occur for a crop.

Soil Moisture Balance

Between wilting point and permanent wilting point actual evapotranspiration is assumed to reduce linearly from the potential rate to zero.

A simple test system



Specified criteria of the test irrigation system

Items	Specified Data		
scheme number	1	2	3
scheme area (ha)	100	100	100
FC (m^3m^{-3}) for sandy soil	0.17	0.17	0.17
PWP (m^3m^{-3}) for sandy soil	0.07	0.07	0.07
secondary canal full supply (m^3/sec)	0.12	0.12	0.12
main canal full supply (m^3/sec)	0.24		
irrigation efficiency	70%		

Length of development stages for beans (Allen et al. 1998)

Days 1-25	Days 26-50	Days 51-80	Days 81-100	Seasonal Total (days)
25	25	30	20	100

Objective function used

Minimise

$$Z = \sum_{j=1}^{m} \sum_{t=1}^{n} X_{tj}$$

where,

X_{tj}	=	*irrigation supply in rotation period t from secondary canal j (mm)*
t	=	*time period number*
j	=	*scheme or canal number*
n	=	*total time periods (days)*
m	=	*number of schemes or canals*

Penalty function 1

If $\theta_{tj} < WP_{tj}$

$$P_1 = \sum_{j=1}^{m}\sum_{t=1}^{n}(WP_{tj} - \theta_{tj})^2$$

The irrigation supply during any time period may be further defined as follows:

$$X_{tj} \quad = \quad N \cdot x_{tj} \cdot IFLAG_{tj}$$

where,

N = *length of time period t (days)*

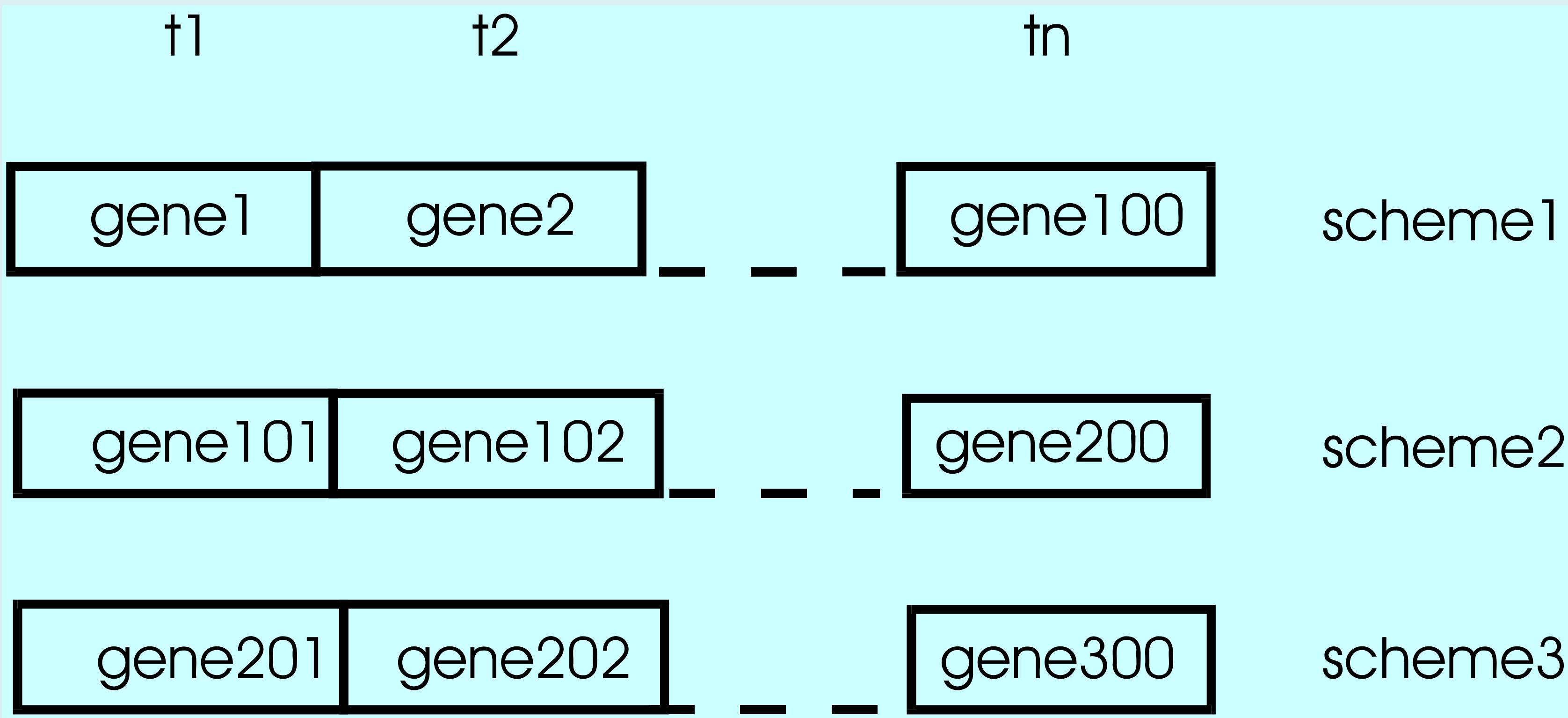
x_{tj} = *irrigation full supply rate to scheme j in time period t (mm/day)*

The Value of IFLAG

$IFLAG_{tj}$ = *0 if scheme j is not being irrigated in time period t*

= *1 if scheme j is being irrigated in time period t*

Decision variable grouping by scheme



Irrigation supply may be expressed in terms of the secondary canal capacity:

$$x_{tj} = Q_{jt}/A_j$$

where,

Q_{jt} = *secondary canal supply to scheme j at time period t*

A_j = *crop area of scheme j*

Canal system capacity constraints have to be considered:

$$\sum_{j=1}^{m} Q_{jt} \leq Qmain$$

where,

Qmain = main canal discharge in time period t

Penalty function 2

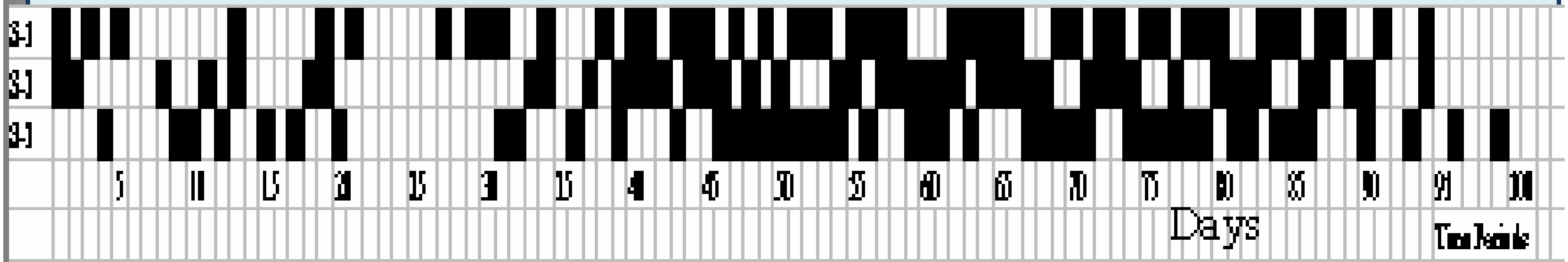
If $\sum_{j=1}^{m} Q_{jt}$ *> Qmain*

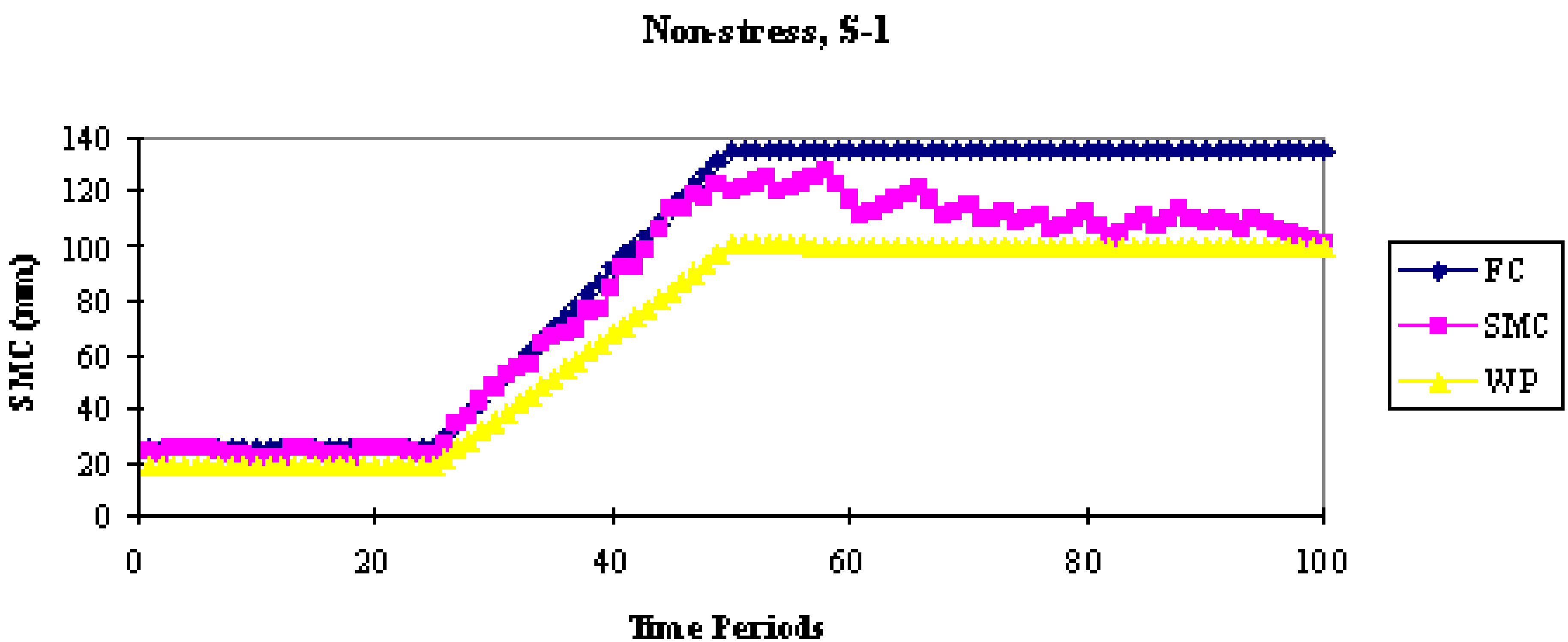
$$P_2 = \sum_{t=1}^{n}\left(\sum_{j=1}^{m} Q_j - Qmain_t\right)^2$$

Scheme water balances
(non-stress case, all values in mm)

Total amount (mm)	Scheme 1	Scheme 2	Scheme 3
Irrigation	304	304	301
ETc	302	302	300
Ea	302	302	300
Change in storage	-1.177	-1.420	-0.580
Drainage	0	0	0

Non-stress case





Scheme water balances (stress case)

Total amount (mm)	Scheme 1	Scheme 2	Scheme 3
Irrigation	231	251	240
ETc	302	302	300
Ea	241	245	238
Ea/ETc	0.80	0.81	0.79
Change in storage	11.428	1.239	0.258
Drainage	1.458	7.780	2.352

Stress Case

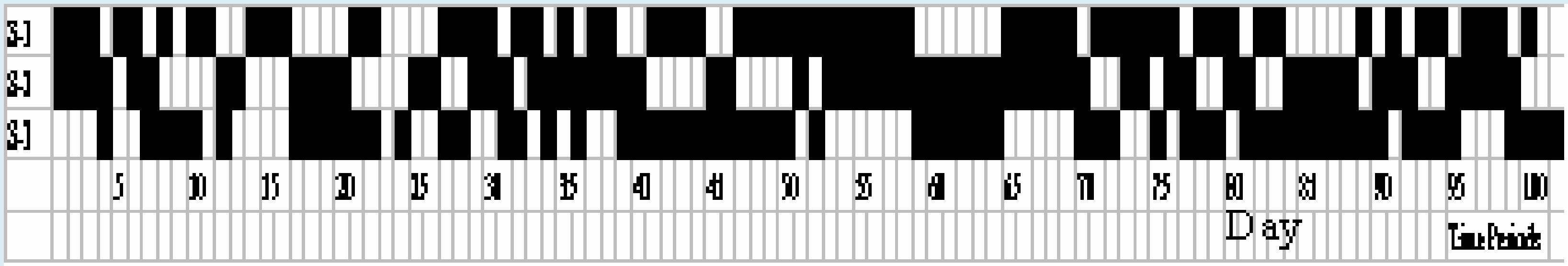
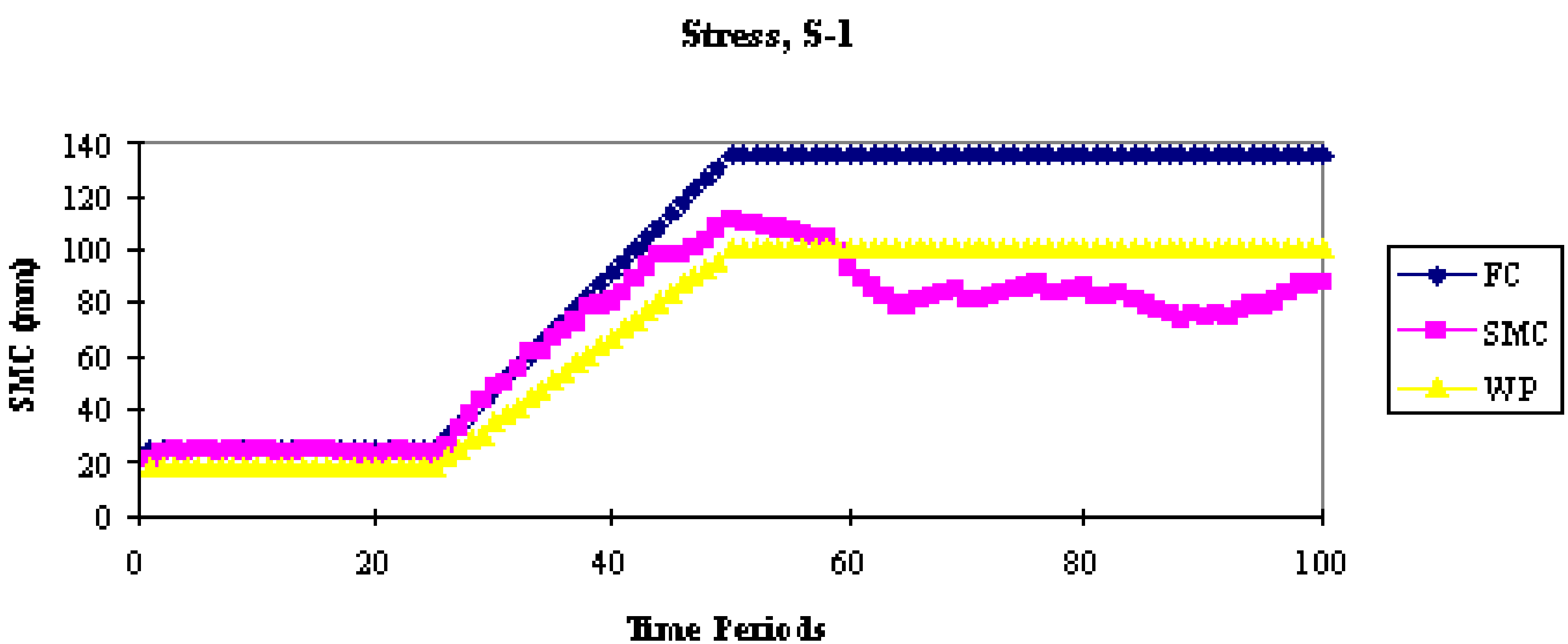


Figure 7 Irrigation schedule generated by GA with water stress



Comparison of soil water stress and non-stress case

Items	Non-stress			Stress		
Avg. supply water (mm/scheme)	303			241		
Cumulative over supply (mm)	0.000			11.6		
Average cumulative stress (mm days)	0.000			658		
Secondary canal	S-1	S-2	S-3	S-1	S-2	S-3
Irrigation days (days)	47	46	46	62	65	63
Irrigation frequency (times)	25	20	22	21	16	18

Publications

- *Wardlaw, R.W., and Bhaktikul, K. 2004. "Application of Genetic Algorithms for Irrigation Water Scheduling". J. of Irrigation and Drainage (ICID), John Wiley & Sons.*
- *Tingsanchali, T., and Bhaktikul, K. 2004. "Application of Genetic Algorithm in Irrigation Scheduling". Proceeding of The International Conference Water India-4 on Water Resource Development- Flood Control, Irrigation, Drinking Water, Water Ways, Electric Power and IOts Transmission System. 3th- 4th Feb, Hotel Hyatt Regency, New Delhi, India. http://www.indiapower.org/events_cwrd.htm*
- *Tingsanchali, T., and Bhaktikul, K. 2003. "Analysis of Ecohydrology of Soil Moisture Balance for Irrigation Scheduling". Proceeding of The 2nd Asia-Pacific Workshop on Ecohydrology. 21st-26th Jul, Cibinong, West Java, Indonesia. http://www.limnologi.lipi.go.id/eco/Sci_ses.htm*

Applications

- *There has not been applied to root zone soil moisture with this modelling in Thailand yet.*

Advantages

- ***GAs have been used for various types of optimisation problems in both linear and non-linear objective functions.***
- ***GAs use population search. It is likely to have local optima less than other search.***
- ***GAs use probabilistic rule.***
- ***GAs can be easily set up and more robust.***
- ***GAs are Black Box Model, not that Conventional Model.***

Advantages

- ***GAs are a Heuristic Optimiser it has less chance to have the butterfly effect.***
- ***It can be used for real time operation.***
- ***Its source codes have been developed successfully for water allocation and scheduling in irrigation systems for equitable manners under scarcity period.***

Registered Software

- *Bhaktikul, K. 2004. “**GAWS-2004**”, Genetic Algorithms for Water Scheduling. Version 2004. Copyright No.80743. Intellectual Property Department, THA.*
- *Bhaktikul, K. and. Wardlaw, R.W. 2004 “**GAWT-2004**”, Genetic Algorithms for Water Scheduling Plus Time Function. Version 2004. Copyright No.80744. Intellectual Property Department,THA.*
- *Bhaktikul, K. and. Wardlaw, R.W. 2004 “**GAWA-2004**”, Genetic Algorithms for Water Allocation. Version 2004. Copyright No.80745. Intellectual Property Department, THA.*
- *Bhaktikul, K. and. Wardlaw, R.W. 2004. “**GAWM-2004**”, Genetic Algorithms for Water Scheduling with Soil Moisture Balance Model. Version 2004. Copyright No.80746. Intellectual Property Department, THA.*
- *Patcharanuntawat, P., and Bhaktikul, K. 2007. “**GACP**”, Genetic Algorithms for Crop Planning Copyright No.157366. Intellectual Property Department, THA.*

Selected AI Publications

- *Wardlaw, R.W., and Bhaktikul, K. 2001. "Application of a Genetic Algorithm for water allocation problem in an irrigation system", J. of Irrigation and Drainage (ICID), 50(2)159-170.. John Wiley & Sons. ISSN 1531-0353.*
- *Wardlaw, R.W., and Bhaktikul, K. 2004. "Comparison of Genetic Algorithm and Linear Programming Approaches for Lateral Canal Scheduling", J. Irrigation and Drainage Engineering, American Society of Civil Engineers (ASCE). 130(4)311-317.*
- *Wardlaw, R.W., and Bhaktikul, K. 2004. "Application of Genetic Algorithms for Irrigation Water Scheduling".*

  J. of Irrigation and Drainage (ICID), John Wiley & Sons.
- *Bhaktikul, K., Soiprasert, S., and Sombunying, W. 2007. "Comparison of Genetic Algorithm and WASAM model for Real Time Water Allocation: A case study of Song Phi Nong Irrigation Project".INWEPF 4th Steering Meeting and Symposium: July 5-7, 2007 The Emerald Hotel BKK, Thailand.*

References

- *Davis,L. 1991. Handbook of Genetic Algorithms. Van Nostrand Renhold, New York.*
- *Goldberg, D.E.1989. Genetic Algorithms in search optimisation&machine learning. Addison-Wesley Publishing Company Inc,USA.*
- *Mays, L.W.(1996). Water Resources Handbook, McGrawHill, USA.*
- *Meadows, D.L. Behrens, W.W.III.,Meadows, D.H., Naill, R.F., Randers, J., and Zahn, E.K.O. (1974). Dynamics of Growth in a Finite World, Wright-Allen Press, Inc. Cambridge, Mass.*
- *Michalewicz, Z.(1992). Genetic algorithms + data structures = evolution programs. Springer–Verlag, New York, Inc., New York.*

References

- *Montaigne, F and Essick, P. (2002). Journal of The National Geographic Society 2(27) 82-113 December (Thai Version).*
- *Wardlaw, R.B., and Sharif, M. (1999). "Evaluation of genetic algorithms for optimal reservoir system operation". J. Water Resour. Plng. and Mgmt., ASCE 125(1), 25-33.*
- *William, W. Metaheuristic Algorithm. Genetic Algorithms: A tutorial power point: free download*

Dedicated……… to Mekong

Thank you

Acknowledgement:
Charles Darwin, Robin Wardlaw, David E. Goldberg,
Pakawan, Kien, Vithet, Thitima
MRC, DWR, RID, MU, SEA START RC, EDU

Inspiration: Darwin's Natural Selection