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Dynamic decision support systems based on Nash bargaining solution for water resources management in a reservoir-river basin

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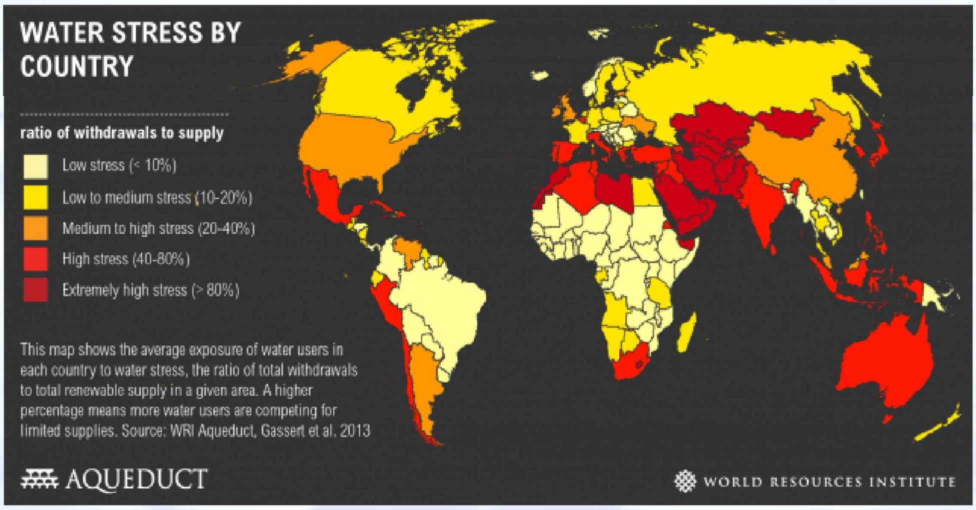
1. INTRO: WATER SHORTAGE IN MALAYSIA

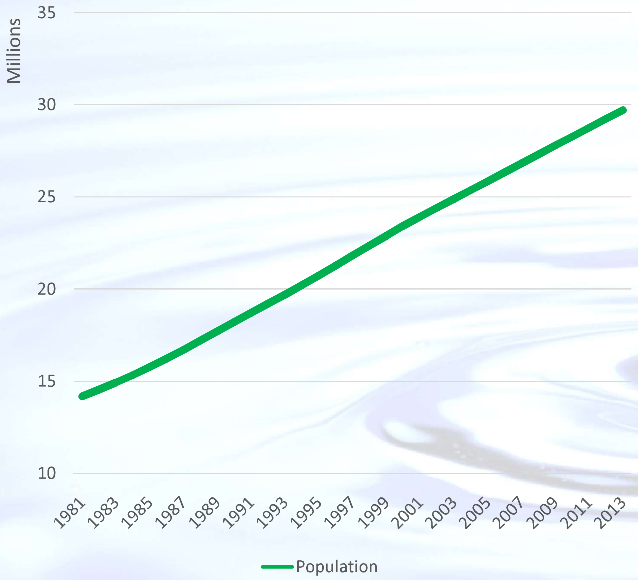
- Malaysia is a humid tropic country
- Averaged Rainfall ≈ 3000 mm/year

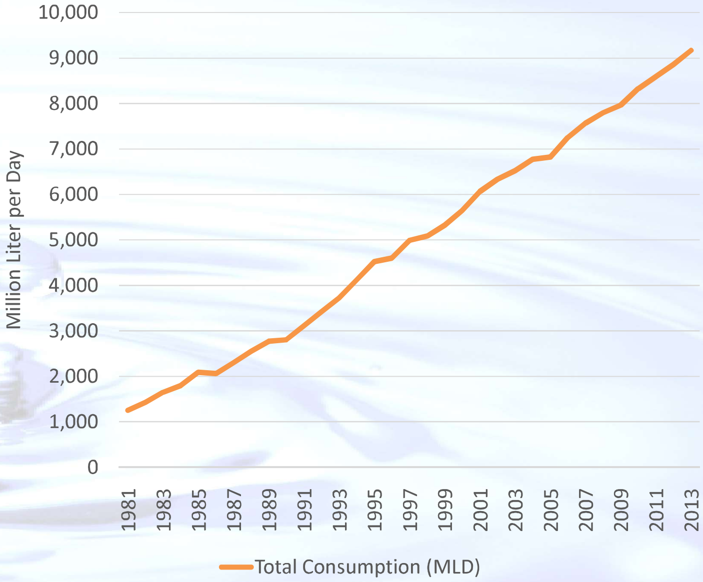
1. INTRO: Water Related issues in Malaysia

- **Rainfall occurrence is not uniform**
  - 2 rainfall seasons (Flood)
  - 2 intermediate seasons (Water Shortage)
  - Water pollutions



Relationship between population increase and water consumption in Malaysia





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(1) INTRO: Water Shortage issues in Malaysia

- **Prolong-drought during intermediate seasons**
  - El-nino phenomenon
  - Extreme weather due to Climate change
- **Increase of demand**
  - Increase of population, urbanization, etc.
  - to meet domestic, industrial, agricultural, and environmental requirements
- **Loss of water resources due to water pollution**
  - caused water treatment plants in Selangor to shut down 42 times last year, disrupting supply to millions of consumers for 2,838 hours (Malaysian Insider, 2015)
- **Management**
  - NRW
  - lack of an efficient DSS for WRM/supply oriented policy to meet increasing demand
  - low water usage efficiency

∴ **An efficient IWRM and optimization system is needed**

(2) Review: Game Theory & Nash Bargaining Solution

- **Bargaining Game** (Von Neumann & Morgenstern, 1944; Kuhn, 1953)
  - recognized as one of the most effective tool for conflict analysis and modelling;
  - A bargaing game is a pair of *(F, d)*;
  - Where F is a set of all the possible utility values to which the players can arrive (U_1, U_2);
  - $d_i = (d_1, d_2)$ is the players preference at disagreement point;
  - U_i is a utility function and indicates players preference and individual risk taking attitudes in the decision process.
- **Nash Bargaining Solution** (Nash, 1953; Harsanyi, 1982)
  - a unique solution of the following optimization model:

Maximize $z = (U_1 - d_1)(U_2 - d_2) \dots (U_n - d_n)$

Subject to $U_i \geq d_1 \quad i = 1, 2, \dots, n$

$\bar{U} = (U_1, U_2, \dots, U_n) \in H$

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(2) REVIEW: Game theory methods/ models

Static game models:

Kuhn, (1953)
Von Neumann and Morgenstern, (1944)
Nash, (1950)
Pataport, (1970)
Longanda and Bhattacharya, (1990)
Mousavi and Ramamurthy, (2000)
Coppla, et al., (2001)
Shahidehpour, et al., (2001)
Palmer, et al., (2002)
Karamouz, et al., (2003)
Shiau and Lee, (2005)
Madani, (2010)
Cardenas, (2013)
Pethig, (2012)
Chang, et al., (2013)
Haimes, (2011)
Kerachian (2014)

Pros: Usually fast and easy to work with
Cons: They do not consider dynamicity of the system

Dynamic game models (discrete form)

Feinerman et al, (1983)
Levhari and Mirman, (1980)
Kennedy, (1987)
Petit, (1990)
Haung et al, (1991)
Fundenberg and Tirolem, (1994)
Batabyal, (1996)
Rubio and Casino, (2001)
Huang, et al., (2002)
Ganji, et al., (2007a, b)

Pros: They consider dynamicity of systems and consider every user while making decision
Cons: Usually are not fast and not easy to work with, due to curse of dimensionality and long run time

Dynamic game models (Continuous form)

Negri, (1989 and 1990)
Dockner and Van Long, (1993)
Martin et al., (1993)
Ligon and Narin, (1997)
Homayounfar et al, (2010, 2011)
Madani, (2013)
Read, (2014)
Ataie-Ashtiani and Ketabchi (2011)
Estalaki, et al., (2015)

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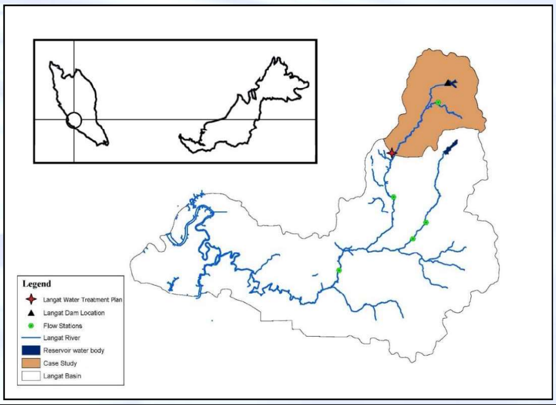
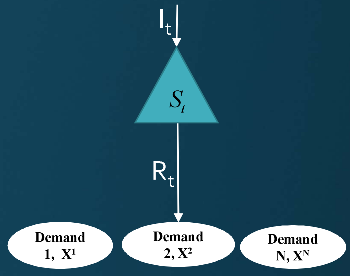
(3A) Model Development (Phase 1): Continuous Dynamic Game Model

- An optimization model for water allocation in a single reservoir system
- Applied to a simple catchment to proof the method developed
  - 7 players/ districts
  - domestic, industrial, & downstream environment requirement



(3A) SEASONAL NON-DISCRETE DYNAMIC GAME MODEL & CORRESPONDING SOLUTIONS



Single reservoir system

Utilities function — To optimize the overall utilities

$$V_t(S_t) = Max_{x^1,\dots,x^n} U_s(x^1, \dots, x^n)_{s.t.} \sum_{j=1}^{n} x^j \le R_t(S_t, I_t)$$

Equation of motion

- $g(S_t, I_t, \varepsilon_t) \equiv S_{t+1} = S_t + (I_t + \varepsilon_t) - R_t$

Stochastic Dynamic Eqn

- $V_t(S_t, \varepsilon_t) = Max_{x_t^1,\dots,x_t^n}, \{U_s(x_t^1, \dots, x_t^n, R_t; t) + \gamma E[V_{t+1}(g(S_t, I_t, \varepsilon_t))]\}$

Nash Bargaining Solution: Utility function of water users $(U_x(x_t^i))$ & reservoir operator $(U_s(S_t))$

- $Intermediate\ Objective\ Function = \prod_{x=1}^{n}(U_{x,t} - d_x) * (U_{s,t} - d_s)$

Collocation method

- $V_t(S_t, \varepsilon_t) \approx \sum_{j=1}^{m} c_j \varphi_j(S_t)$

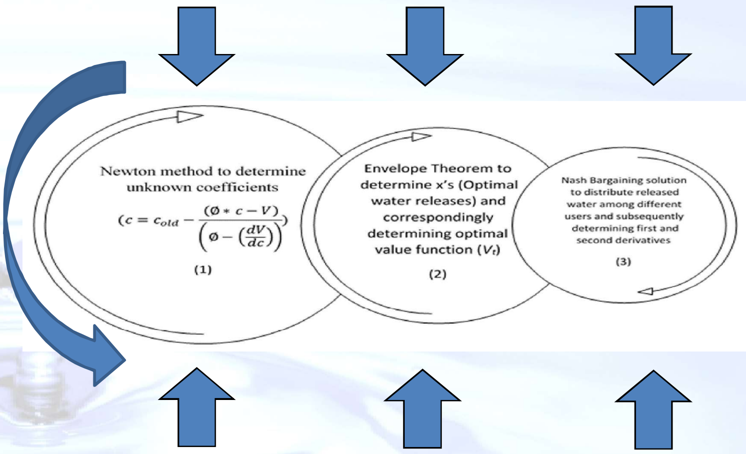
Newton Method & Envelop theorem is used to compute this optimization problem

- $\sum_{j=1}^{m} c_j \varphi_j(S_t) = Max_{x_t^1,\dots,x_t^n}, \{U_s(x_t^1, \dots, x_t^n, R_t; t) + \gamma E[\sum_{j=1}^{m} c_j \varphi_j(g(S_t, I_t, \varepsilon_t))]\}$ (*)

(3A) Trial and error method

Newton Method

$$c = c - \frac{(\phi * c - v)}{(\phi - v'(c))}$$



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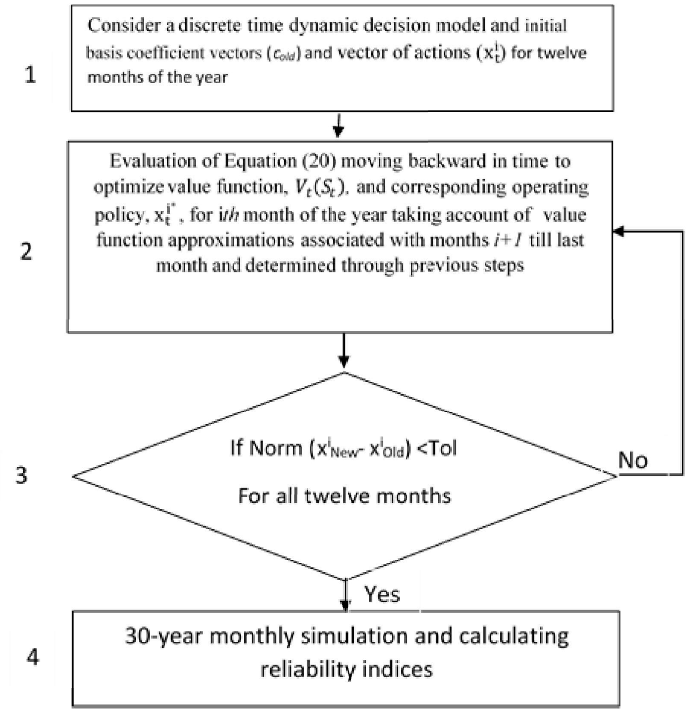
(3A) Model Structure for connecting different seasons together

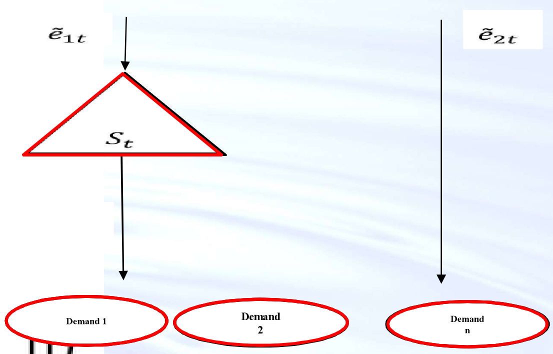


(3A) Decoupled Reservoir-River System

Seven players:

$$\sum_{j=1}^{m} c_j \varphi_j(S_t,\varepsilon_{1t}) = Max_{x_t^1,\dots,x_t^n}\Big\{U_s(x_t^1,\dots,x_t^n,R_t,I_{2t},\varepsilon_{2t};t) + \sum_{k=1}^{l}\Big[\sum_{j=1}^{m} w_k c_j\varphi_j(g(S_t,I_{1t},\varepsilon_{1t}))\Big] + \sum_{Mi=M+1}^{12}\Big[\sum_{k=1}^{l}\Big[\sum_{j=1}^{m} w_k c_j\varphi_j(g(S_t,I_{1t},\varepsilon_{1t}))\Big]\Big]\Big\}$$

Decoupled system



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(3B) Case Study

Why Langat River Basin ???

- **Pass through 3 distinct administrative regions**
  - Federal Territory of Putrajaya and Cyberjaya
  - Selangor State
  - Negeri Sembilan State

- **Main source of water supply to strategic cities**
  - Kuala Lumpur (capital city with highst population density)
  - Putrajaya (administrative centre with highest population growth)

- **3 major Water Resources problems**
  - Flood, Water pollution, Drought/ Water shortage

(3B) CASE STUDY

Reasons:

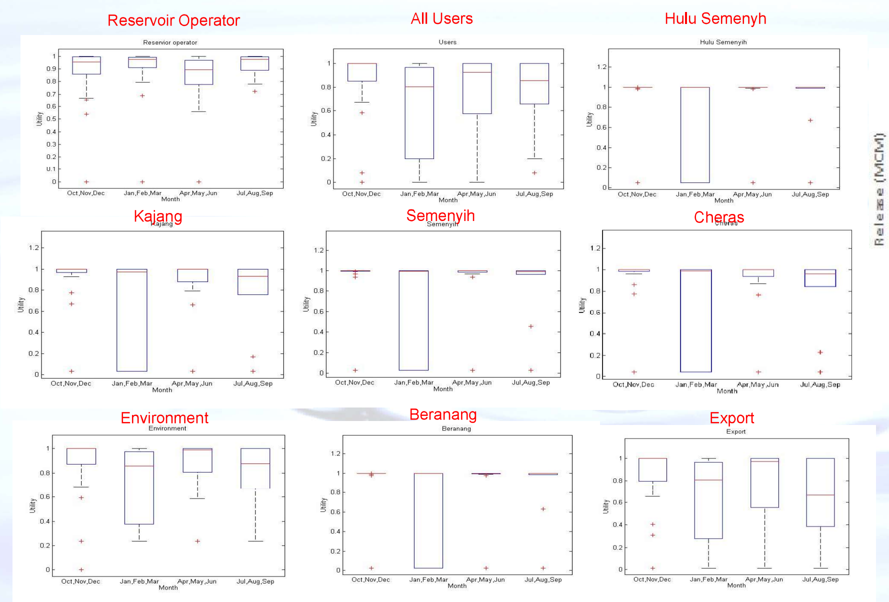
- Data Limitation
- Population Density
- Location of Water Treatment Plans
- Location of Dams
- Etc.

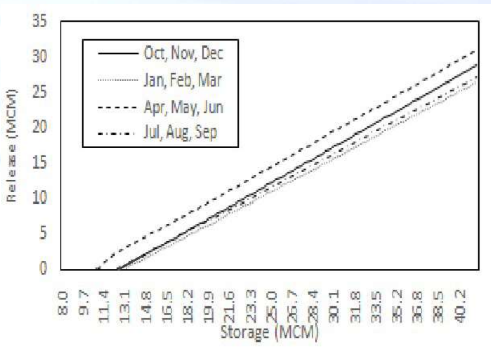
(3C) DATA COLLECTION

Data Type	Data Required	Related Agencies
Surface Water	Rainfall station data (400 stations with 15 minutes interval data in Malaysia, all station with at least 10 years of record)	Drainage & Irrigation Department (DID)
	Streamflow data (Depth, Velocity, and Discharge for all monitoring stations along all major river in Malaysia)	DID
	Water treatment plants (location, coordinate, capacity, etc)	Selangor Water Management Authority (SWMA/LUAS)
	Daily water release from Reservoir	SWMA Puncak Niaga
	Water/ Storage level of reservoir (continuous data)	SWMA Puncak Niaga
	Reservoir and dam physical properties (height, spillway, capacity, etc.)	SWMA Puncak Niaga
Water Supply	Treat water	SYABAS, ABASS
	Raw water (Surface and groundwater abstraction)	LUAS, JMG
Digital data/ GIS Maps	Satelite image	Department of Survey and Mapping Malaysia (JUPEM)
	Catchement map	JUPEM
	Land use maps	JUPEM
	Soil maps	JUPEM
	Rivers, reservoirs map	JUPEM
	Hydrogeology map	Minerals and Geoscience Department Malaysia (JMG)
	Population	Department of Statistic Malaysia (DOSM)

(3D) Results

utilities of reservoir and water users based on optimal reservoir operation rules





Operating policy resulting from collocation solution for four seasons

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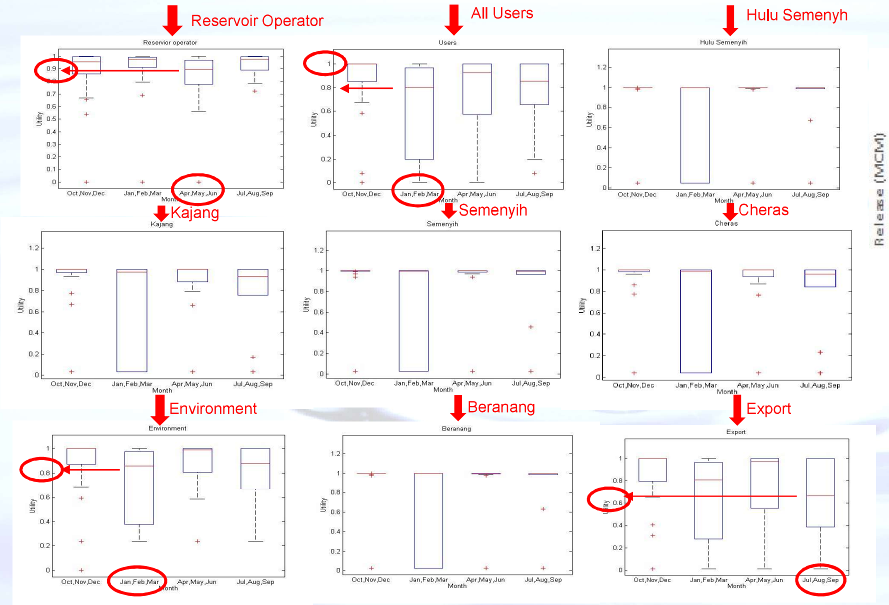
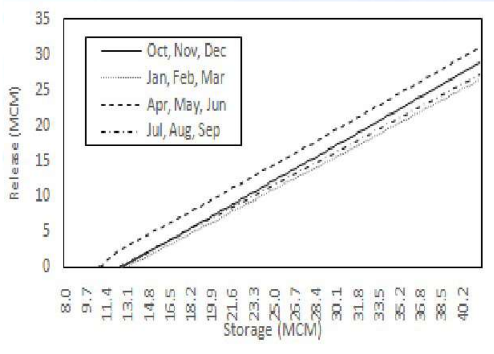
(3D) Results

utilities of reservoir and water users based on optimal reservoir operation rules





Operating policy resulting from collocation solution for four seasons

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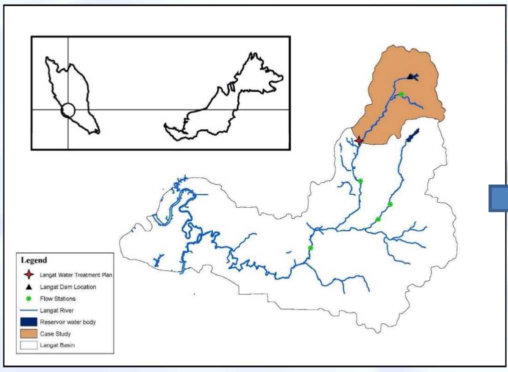
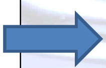
(4A) Model Development (Phase 2): Coupled System Dynamic and Game Model

(Zomorodian et al., 2017; Zomorodian et al., 2018)

- An extended model: Larger area, multi reservoir system
- An integrated dynamic simulation and dynamic optimization model
- To study the interactions and feedbacks between components
- To study future conditions when different managerial scenarios are implemented.





Reasons:

- Data Limitation
- Population Density
- Location of Water Treatment Plans
- Location of Dams
- Etc.

(4A) System Dynamics

Objective(s)	Citation, Location
Sustainable water planning and management	Duran-Encalada et al. (2016), Gastélum et al. (2010), US–Mexico border region; Dawadi and Ahmad (2013), US; Xiong et al. (2015), Chang et al. (2015), Liu et al. (2014), Dan and Wei-shuai (2012), Li et al. (2011), Wang et al. (2011), China; Zarghami and Akbariyeh (2012), Iran; Scarborough et al. (2015), Australia; Xi and Poh (2013), Singapore; Madani and Mariño (2009), Mirchi et al. (2012), Mirchi et al., (2010), US
Global environmental analysis	Akhtar et al. (2013), Davies and Simonovic (2011), Canada
Performance analysis and risk assessment	Gohari et al. (2014), Gohari et al. (2013), Iran; Madani and Mariño (2009), US; Wu et al. (2013), China
Water quality monitoring and analysis	Liu et al. (2015b), China
Reservoir system management	Hassanzadeh et al. (2014), Canada; Mereu et al. (2016), Italy; Mereu et al. (2016), Italy; Gohari et al., (2013), Ghashghaie et al. (2014), Iran
Developing a learning tool for decision-makers	Kotir et al. (2016), Ghana; Sahin et al. (2015), Australia; Faezipour and Ferreira (2014), US

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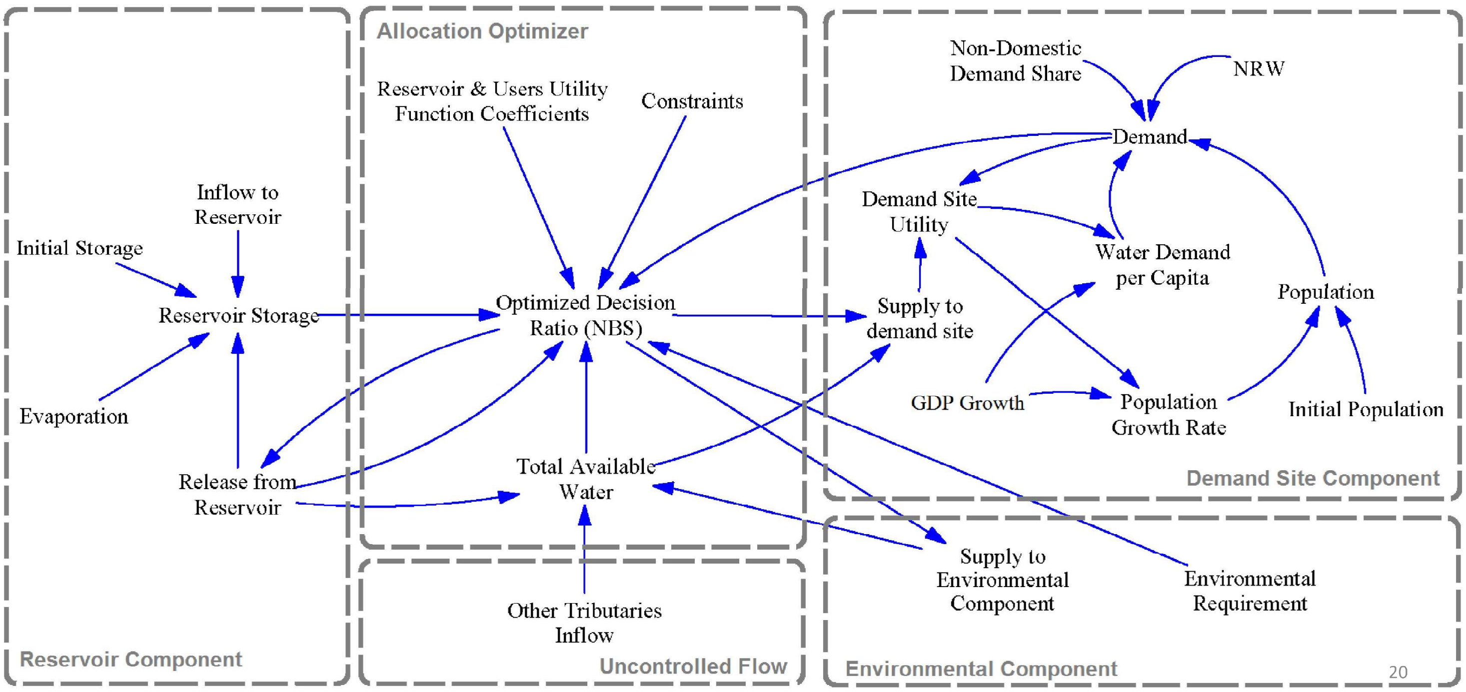
(4A) CLD models of different components and their interactions



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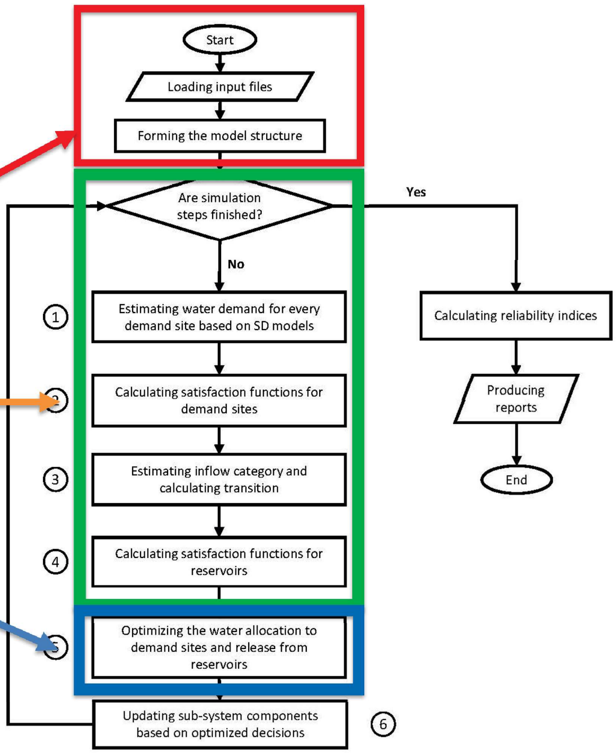
(4A) Modeling Flowchart

Initialization

Simulation

Optimization



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(4A) R-R-V Indices

- $R_n = \left(1 - \frac{\text{Number of failures in design period}}{\text{Length of design period}}\right) \times 100$
- $R_{v-s} = \frac{\text{Total storage shortfall or overflow}}{\text{Total available water into reservoir during planning horizon}}$
- $R_{v-d} = \frac{100}{n} \sum_{i=1}^{n} \left(\frac{Supplied\ Water}{Demand}\right)$
- $Res = \left(\frac{1}{F} \sum_{j=1}^{F} d(j)\right)^{-1}$
- $Vul = \frac{1}{F} \sum_{j=1}^{F} v(j)$

- **Reliability** is the capability of a system or sub-system to perform its mandatory tasks under the required conditions for a specified period of time
- **Resilience** shows how fast a system is likely to recover and return to a satisfactory state after a failure event
- **Vulnerability** denotes the possible damage of a failure if it occurs. It is important to consider the potential consequences of a failure, even if the possibility of a failure event is small

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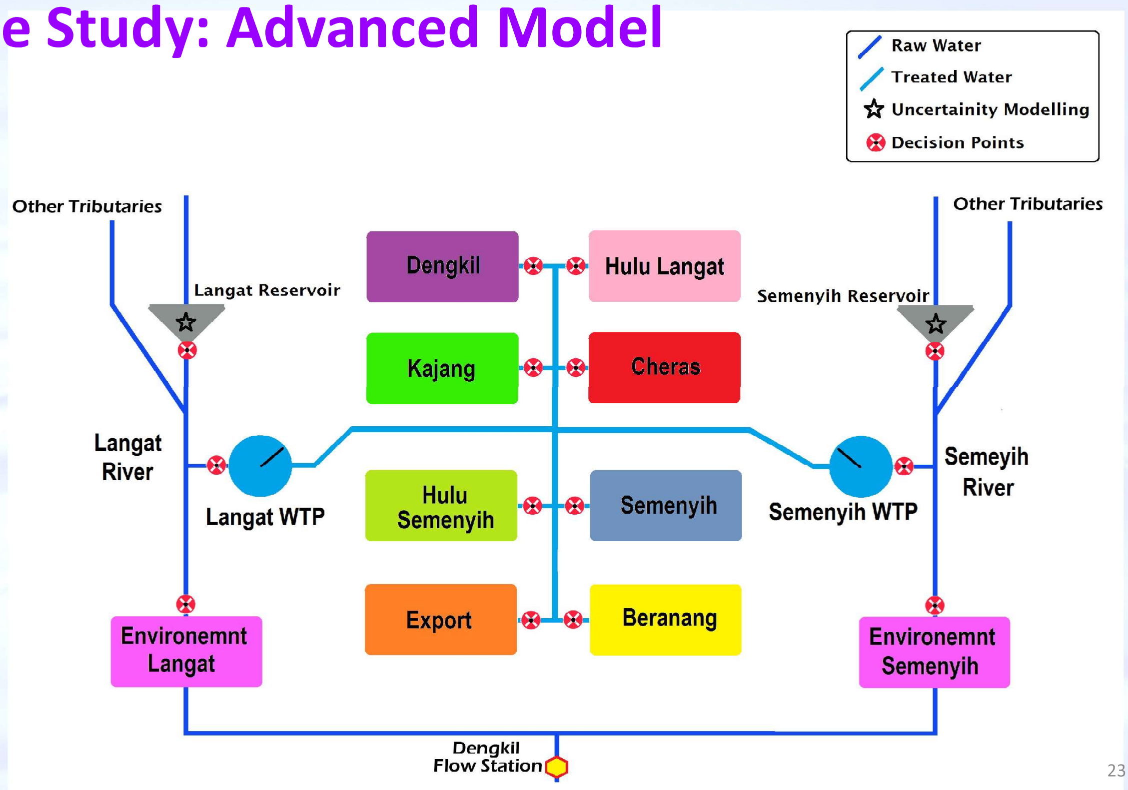
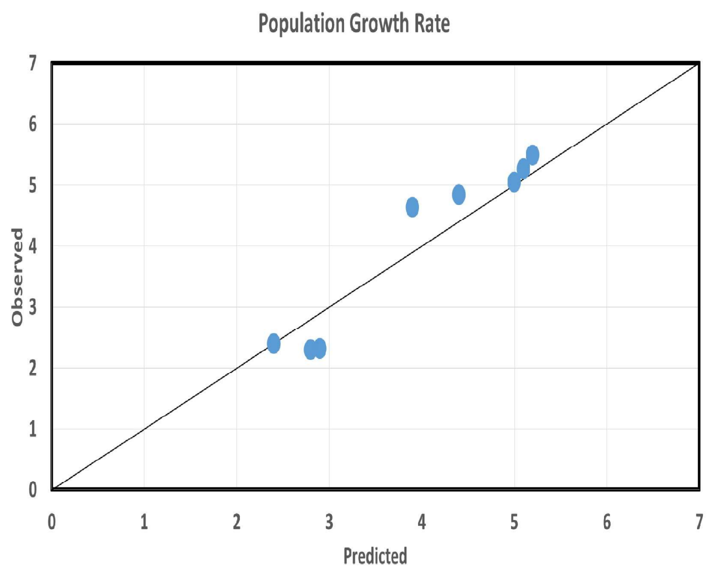
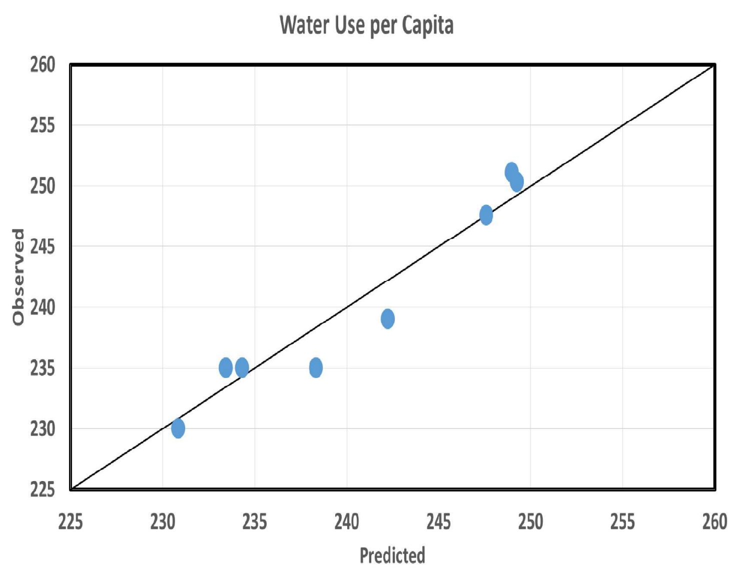
(4B) Case Study: Advanced Model



(4C) Results: SD Model Calibration

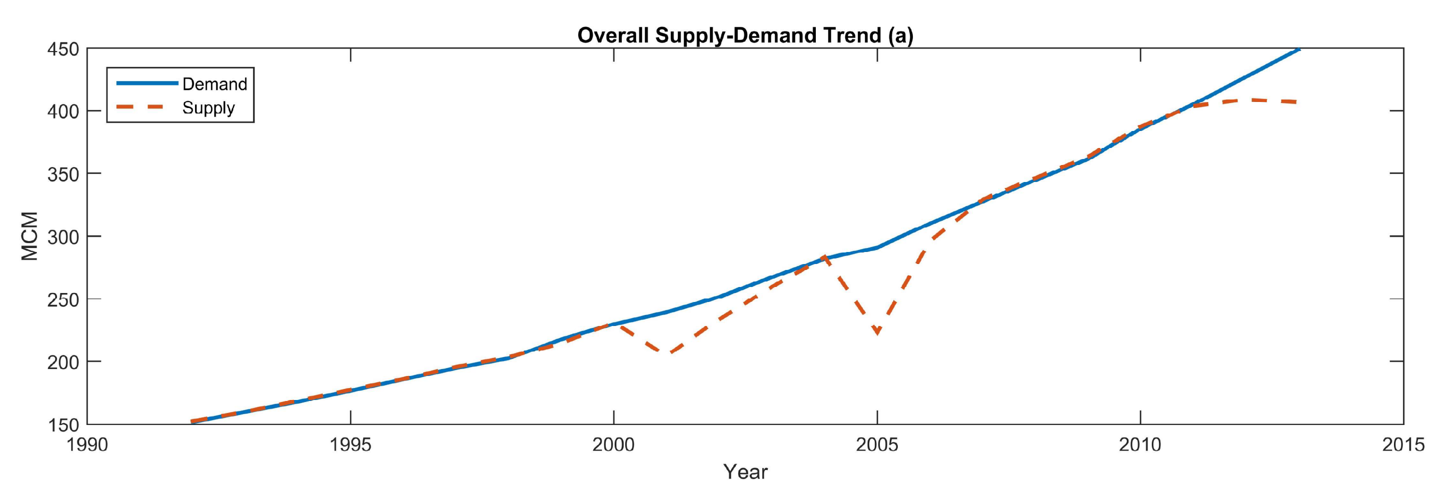
- For a period of 8 years (2006-2013)





(4C) Results: Total Supply-Demand Trend

- Model evcaluation from 1992-2013



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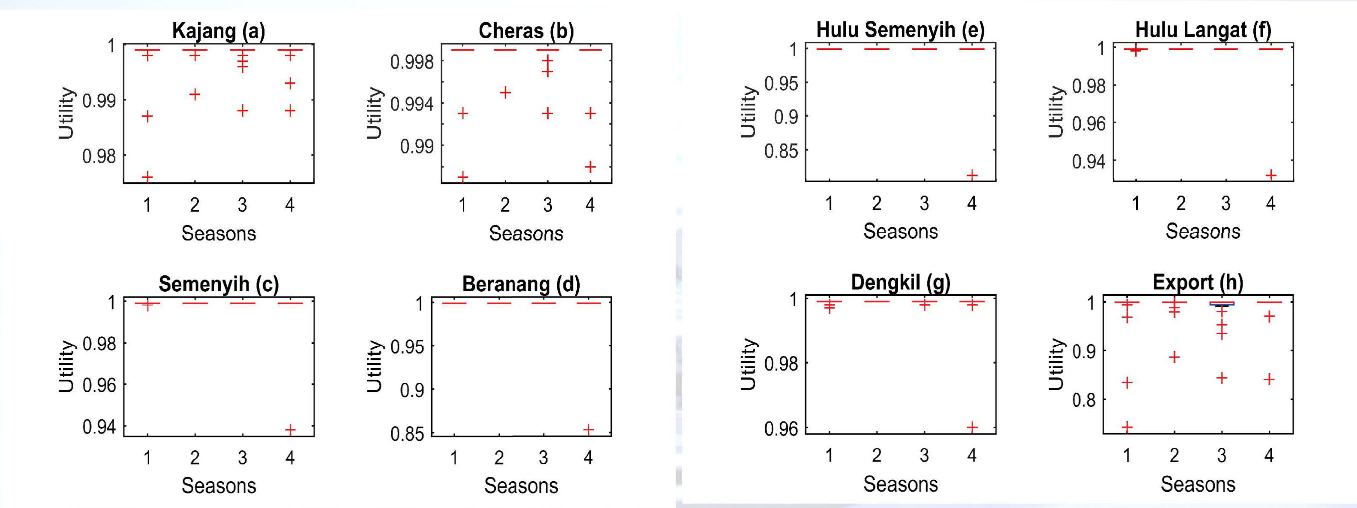
(4C) Results: Satisfaction Level



- Averaged satisfaction level for all demand sites = 99.73%
- The only incident <80% @ Export site

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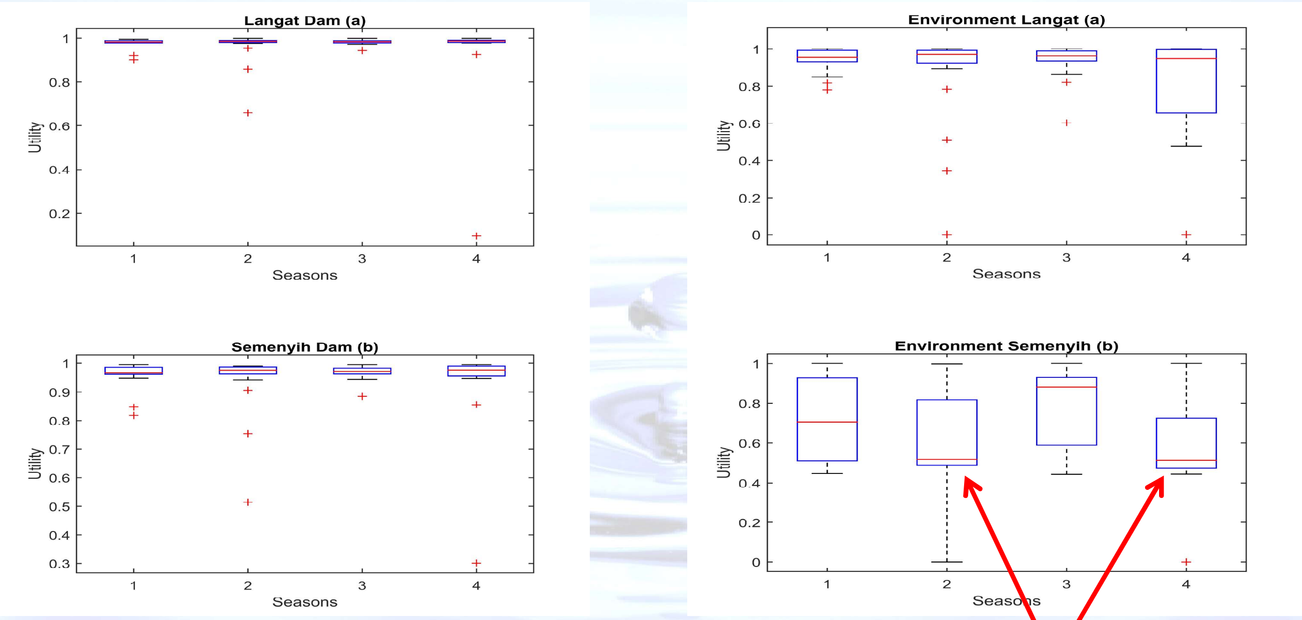
(4C) Results: Satisfaction Level



The averaged satisfaction level for Langat reservoir (97%) and Semenyih Reservoir (95%)

Flood at downstream

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(4C) Results: Performance of Extended Model

Component	Occurrence Reliability	Volumetric Reliability	Resilience	Vulnerability
Kajang	90.9	99	50	2.225
Cheras	93.2	99.4	50	1.517
Semenyih	98.9	99.7	100	0.97
Beranang	98.9	99.5	100	0.42
Hulu Semenyih	98.9	99.5	100	0.12
Hulu Langat	98.9	99.7	100	0.93
Dengkil	97.7	99.7	100	0.645
Export	83	95.7	46.7	25.627
Environment Langat	96.6	99.5	66.7	5.57
Environment Semenyih	94.3	98.5	40	25.29
Langat Dam	98.9	0.005	100	9.06
Semenyih Dam	98.9	0.001	100	3.64

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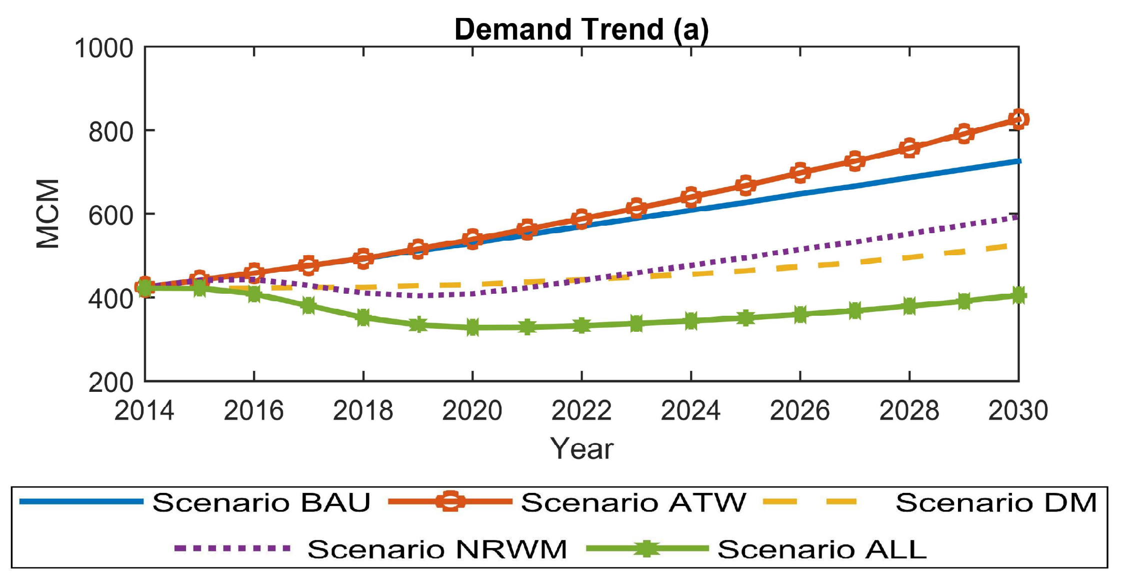
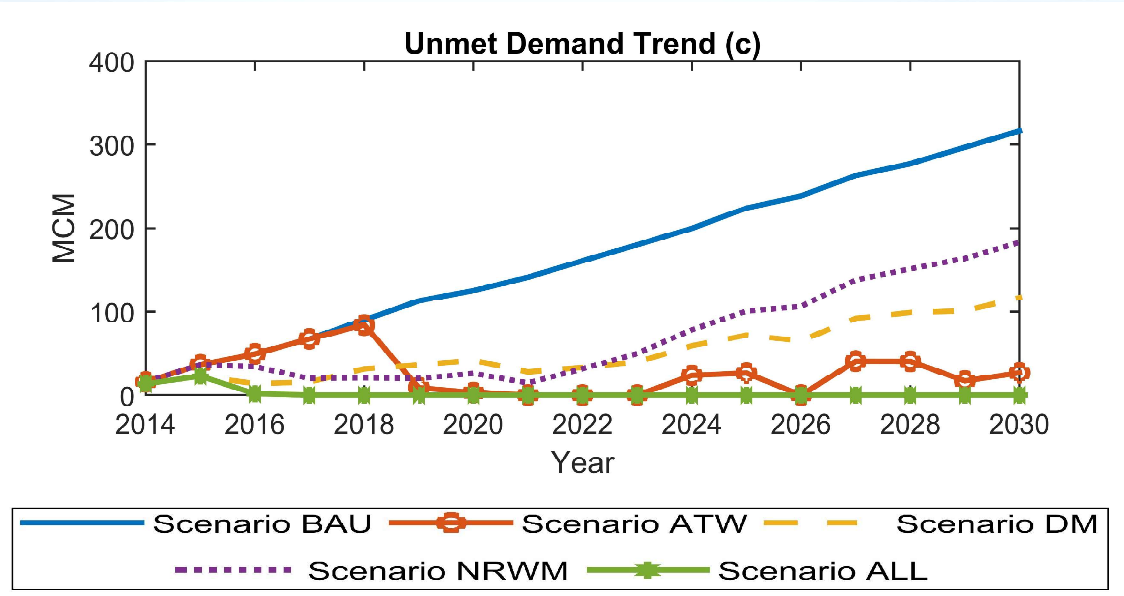
(4D) Scenario Analyses

1. **Reference (Business as usual): BAU**
2. **Additional Treated Water: ATW**
   – Langat2 WTP (1130 MLD)
   – Pahang-Selangor water transfer project (299MCM)
3. **Demand Management: DM**
   – WUPC reduction from 240-230 to 160-170 lit/day/capita
4. **Clean Water Conservation: NRWM**
   – NRW reduction from 33.6% to 5%
5. **Three Scenarios Combined: ALL**
   – Combination of 2, 3 and 4

(4D) Scenario Analysis: Demand



(4D) Scenario Analysis: Unmet Demand



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(5) Conclusion

Model 1:

- Reduce runtime significantly compared to discrete dynamic game models, due to the continuous nature of the interconnected variables.
- The overall storage reliabilities of the reservoir system is increased. volumetric reliabilities improved over the year in comparison with annual alternatives
- The Seasonal operating rules resulted from the presented models are more practical in comparison with annual alternatives; and it is closer to reality with dynamic structure, and account of inflows & the rest-of-the-network flow uncertainty

Model 2:

- helps the decision-maker to follow up the consequences of his/her decisions in the long-term.
- The method was capable of modeling different aspects of a water resource system and could handle possible conflicts over limited available water.
- The model is able to simulate and optimize water resources management in the river basin successfully
- Results from Scenario analyses showed that supply-oriented policies are temporary solutions
- Combine demand management and non-revenue water management, on top of additional treated water is an effective alternative to ensure sufficient water supply in future.

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рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
спасибо
faafetai lava
mersi
barka
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tack
spas
kia ora
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
mahalo
tapadh leat
kiitos
dankie
nanni
nandri
dhanyavad
thank you
gracias
хвала
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gràçie
hvala
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köszönöm
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terima kasih
rahmet
kam sah hamnida
rahmat
ευχαριστώ
diolch
dhanyavadagalu
shukriya
mercê
мерси
তোমাকে ধন্যবাদ
감사합니다
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