HARVARD UNIVERSITY
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

Singapore's Water Trade with Malaysia and Alternatives

By Diane Segal

March 30, 2004

Acknowledgment

I would like to express my deep gratitude to Professors Aaron T. Wolf, from Oregon University, John Thomas and Dave Brown from Harvard University and to Buck Song Koh, Mid-Career student at the Kennedy School of Government and journalist from Singapore, for helping me in my search for information and for their insights. I would especially like to thank my supervisor, Professor Henry Lee, for making himself available for long discussions and for his invaluable dedication to this project.

Data and information used in this analysis were drawn from the literature publicly available or off the web, essentially from the Singapore Ministry of Foreign Affairs, the Malaysian Ministry of Foreign Affairs, the Singapore Statistics Department, the Public Utilities Board of Singapore, and from online newspapers. Best estimates based on case study were used when necessary.

Table of Content

Abbreviations and Acronyms **4**
Unit Conversion **5**
List of Tables **5**
List of Boxes **5**
List of Figures **5**
Executive Summary **6**
Report **7**
Introduction 7
Framework 10
Analysis 11
Institutional Framework and Performance of the Water Sector in Singapore 11
Projected Water Demand and Available Resources in Singapore 13
Negotiations of Water Trade with the State of Johor 15
Storage Capacity and Rainwater Collection 22
Wastewater Re-Use 23
Desalination 25
Developing Water Trade with Other Countries 29
Other Water Conservation and Protection Measures 31
Controlling Water Demand 32
Recommendations and Conclusions 34
References 41
Appendices 42
Appendix I. Map of Singapore and surrounding, and its river system 42
Appendix II. Reservoirs and Water Treatment Works in Singapore 43
Appendix III. Projections of Water Demand in Singapore 44
Appendix IV. Desalination Technologies 49
Appendix V. Foreign Sources of Water for Singapore 53

Abbreviations and Acronyms

ADB	Asian Development Bank
ASEAN	The Association of Southeast Asian Nations (ASEAN) comprises Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam.
BOOT	Build-Own-Operate-Transfer
ED	Electrodialysis
EDR	Electrodialysis Reversal
IDA	International Desalination Association
IDSS	Institute of Defense and Strategic Studies
LT-TVC	Low-Temperature Thermal Vapor Compression
MED	Multiple-Effect Distillation
MED-TVC	Vapor Compression
MFA	Ministry of Foreign Affairs
MSF	Multi-Stage Flash Distillation
MVC	Vapor Compression
O&M	Operation and Maintenance
PUB	Public Utilities Board
RO	Reverse Osmosis desalination plant
SAF	Singapore Armed Forces
UFW	Unaccounted For Water
W/P	Water/Power ratio

Measurement Units

km	kilometer
^{o}C	Degree Celsius
cents/m^3	US cent per cubic meter
cm	cubic meter
^{o}F	Degree Fahrenheit
gal	gallon
kWh	Kilowatt-hour
m^3	cubic meter
m^3/d	cubic meter per day
mcm	million cubic meter
mg	million gallon
mgd	million gallon per day
mg/l	milligram per liter (note: 1 mg/l = 1 ppm)
ppm	parts per million (note: 1 ppm = 1 mg/l)
US$/m^3	US dollar per cubic meter

Unit Conversion

Measurement	
1 gallon	4.546 liters
1,000 gallons	4.546 m^3
1 mile	1.609 km
Currencies	
1 Singapore dollar	100 Singapore cent
1 Malaysian Ringgit	100 Malaysian sens
1 Malaysian sen	0.47 Singapore cent
1 Singapore dollar	0.6 US dollar

List of Tables

Table 1. Water Resources of ASEAN Countries
Table 2. Water prices (in US$) in some ASEAN countries
Table 3. Performances of the Public Utilities Board of Singapore
Table 4. Estimated Current and Projected Water Demand in Singapore (million m^3/year)
Table 5. Agreements governing Singapore-Malaysia water trading
Table 6. Singapore's Reservoirs and Current Storage Capacity
Table 7. Build-Own-Operate-Transfer Contract Costs for Desalination Projects
Table 8. Water Tariffs in Singapore as at 31 December 2002
Table 9. Unit cost of various water supply alternatives and quantity currently supplied or to be supplied in Singapore
Table 10. Developing Singapore's independence from Johor's water supply

List of Boxes

Box 1. Basic Information about Singapore
Box 2. Difficulties Faced by Water Talks between Singapore and Malaysia to Renew their Water Contracts
Box 3. Singapore's history and economy in a nutshell
Box 4. Quotes illustrating political tensions between Singapore and Malaysia on the water issue
Box 5. Ongoing disputes between Malaysia and Singapore

List of Figures

Figure 1. Water Trading between Singapore and Malaysia
Figure 2. Schematic of a desalination process
Figure 3. Estimated Current Water Supply Curve in Singapore
Figure 4. Estimated 2011 Water Supply Curve in Singapore

Executive Summary

Singapore is a water-stressed country which currently relies on Malaysia to receive half of its daily water consumption[1]. It buys freshwater from the State of Johor, Malaysia, treats it and sells back part of it to Johor as treated water. The day Singapore separated from Malaysia in 1965, water trade between these two countries became the object of fierce dispute. This study addresses Singapore's vulnerability vis-à-vis its water supply from Malaysia and lays out possible strategies to assist Singapore in its water policy making. Striking the right balance between full independence to cover its water needs and trading with neighbors is a challenging task. The political, technical and economic feasibility of various water supply alternatives available to Singapore are discussed in the present paper. The primary recommendation is to diversify water resources while staying engaged in water trading with Malaysia since this is their cheapest option. Achieving full independence vis-à-vis Malaysia might not be worth the cost considering that breaching water agreements would be costly to Malaysia, meaning that the probability of a cut in Johor's water supply is low. Singapore has the double advantage of being a buyer and a seller of cheap treated water for Malaysia which gives him some leverage in water negotiations. In addition, Malaysia benefits from large investments from Singapore. The second recommendation is to continue current efforts in promoting water recycling, controlling water demand, and protecting the quality of Singapore's freshwater.

[1] IDSS, 2002.

Report

Introduction

Water is a key issue in national security, not only to provide the minimum amount of drinking water vital to a country's population, but also to maintain its industries and other economic activities. Singapore is considered a water-stressed country due to insufficient resources[2]. The ratio of its domestic water supply to demand is the lowest among ASEAN countries, as expressed by the annual withdrawals as percentage of its water resources (see Table 1).

Table 1. Water Resources of ASEAN Countries

Country	Annual internal renewable resources (km^3)	Annual withdrawals (km^3)	Annual per capita internal renewable water resources (m^3)	Annual withdrawals as %-age of water resources	Annual per capita groundwater withdrawal (m^3)	1999 GNP per capita (US$)	Population (millions)
Cambodia	88.10	0.52	8,195	1	-	300	11.0
Indonesia	2,530.00	16.59	12,251	1	-	1,110	209.4
Laos	270.00	0.99	50,392	0	-	400	5.4
Malaysia	456.001	9.42	21,259	2	-	4,530	23.0
Myanmar	1,082.00	3.96	22,719	0	-	-	48.9
Philippines	323.00	29.50	4,476	9	82.8	1,200	75.8
Singapore	0.60	0.19	172	32	-	32,810	3.9
Thailand	110.00	31.90	1,845	29	15.0	2,740	62.6
Vietnam	376.00	28.90	4,827	8	-	310	80.3

Sources: World Resources Institute 1998; The Little Data Book, World Bank 1999; and Asiaweek 2000.

About half of Singapore's freshwater daily consumption is currently provided by Malaysia[3], the other half comes from domestic reservoirs and stormwater collection ponds[4] (see Appendix I and II for a map of Singapore's river systems and reservoirs). The provision of water from Malaysia is regulated by agreements. Yet, this provision is uncertain due to political tensions between the countries. There is a risk of cut-off,

---

[2] IDSS, 2002, p. 35.
[3] IDSS, 2002, p.4.
[4] "3 water plants for Singapore by year 2001" In *The Straits Times*, 4 May 1998.

announced or sudden, of water supplies from Malaysia, which enhances Singapore's vulnerability. Water demand in Singapore has been increasing at a rate of about 4%[5] over the past decade due to its population increase and economic development. The government of Singapore needs to develop a strategy to ensure that its water supply will match its future growing water needs and to minimize its vulnerability towards the Malaysian supply.

The appropriate national water policy will strike a balance between (1) minimizing political risks related to relying on foreign countries for water supply by developing domestic supplies and diversifying its water sources, and (2) minimizing the economic cost of developing these water supply alternatives designed to achieve some level of independence.

Minimizing the cost of water supply is important not only for residents but also for the industries thriving in Singapore's territory. The cost of water supply is reflected in water pricing. Too high water prices might erode some of Singapore's industrial competitiveness. As can be seen from Table 2, Singaporean's water price for industries is already amongst the highest of the ASEAN countries.

This report presents various water supply alternatives available to Singapore along with their estimated costs. Projections and analyses will pay particular attention to the key deadline of 2011, which is the expiration date of the first water agreement between Singapore and Malaysia. Policy recommendations for Singapore will be derived from these analyses.

---

[5] Based on total water sales, increasing from 322.80 billion m^3 in 1990 to 439.68 billion m^3 in 1999. Data source: Department of Statistics, Singapore.

Table 2. Water prices (in US$) in some ASEAN countries

Country	Domestic	Industrial
Cambodia (a)	0.091/m^3 – Flat rate	0.256/m^3 – Flat rate
Indonesia (b)	0.157 to 0.744/m^3	0.474 to 1.008/m^3
Laos (c)	0.49/month under 6m^3 0.117 to 0.171/m^3	2.35/month under 16m^3 0.171 to 0.191/m^3
Malaysia (d)	0.119 to 0.456/m^3	0.330 to 0.634/m^3
Myanmar (e)	0.809 to 1.618/m^3	0.809 to 1.618/m^3
The Philippines (f)	0.14 to 0.47/m^3 plus a fixed charge of 1.12	0.55 to 0.67/m^3 plus a fixed charge of 5.50
Singapore (g)	0.39 to 0.82/m^3	0.82/m^3 – Flat rate

Data source: ADB, 1997.

Whenever water utilities use a step-wise tariff structure based on the volume of water consumed, and when each utility charges different tariffs, the range of prices given in this table covers all consumption rates and various utilities for which data were available.

(a) Cambodia water utility: Phnom Penh Water Supply Authority. Tariffs effective June 1994.
(b) Indonesia water utilities: Pdam Dki Jakarta (Pam Jaya). Tariffs effective July 1994.
(c) Laos water utility: Nam Papa Lao (Lao Water Supply Authority). Tariffs effective July 1996.
(d) Malaysia water utility: Syarikat Air Johor SDN. BHD. (Johor Water Company). Tariffs effective April 1991.
(e) Myanmar water utility: Mandalay City Development Committee. Tariffs effective August 1996.
(f) Philippines water utility: Metropolitan Waterworks and Sewerage System (in Manila). Tariffs effective August 1996.
(g) Singapore water utility: Public Utilities Board. Tariffs effective March 1995. Note: Although updated, 2002, tariffs were used in the remaining of this paper, 1995 tariffs are given in this table for Singapore for the sake of comparison with data from other ASEAN countries available for years 1994 to 1996.

Box 1. Basic Information about Singapore

The Republic of Singapore is an island country at the southern tip of the Malay peninsula. It consists of the large Singapore Island and 58 small islands, 20 of which are inhabited.

Singapore has a hot, humid climate. Temperatures are high and rainfall is heavy throughout the year.

Area:	239 sq miles (618 sq km)
Population:	4.3 million (as of 2002)
Capital (Population)	Singapore City (3.86 million)
Government	Multiparty Republic
Ethnic Groups	Chinese (77%), Malay (14%), Indian (7%)
Languages	Chinese, Malay, Tamil and English (all official)
Religions	Buddhist (Chinese), Muslim (Malays), Christian, Hindu, Sikh, Taoist, Confucianist
Currency	Singapore Dollar = 100 cents

Data source: Atlas of the World (2002) Tenth Edition, Oxford University Press, p. 25.

Framework

The challenge facing Singapore officials is (1) to lower the State's vulnerability to a potential cut-off of water supplies from Malaysia and (2) to ensure that Singapore meet its future water demand. Officials need to assess the likelihood of a partial or complete cut-off of Malaysian supply, identify what the best alternatives would be in each case based on cost-benefit analyses, and develop these alternatives accordingly.

After assessing the current and projected water situation of Singapore, the following water resources management alternatives are presented in this paper:

- Negotiating new water trade agreements with the State of Johor, Malaysia.
- Storage capacity and Rainwater harvesting
- Wastewater re-use
- Desalination
- Developing water trades with Indonesia and possibly other regions, bringing water via submarine pipelines or via water tankers.
- Additional water conservation and protection measures such as reducing the unaccounted for water[6] (UFW), setting a secondary water distribution system for "grey water", encouraging water saving in agriculture, and protecting the quality of existing freshwater resources.
- Controlling water demand

Some options might be more appropriate for daily water supply, others could be used in case of an emergency. To do a cost-benefit analysis, one would have to assess the actual

[6] UFW (%) = Total annual production (m^3) – [Total annual consumption (m^3) × 100 / Total annual production (m^3)]

costs and opportunity costs of each alternative, their environmental, social and political impacts, their institutional, legislative and regulatory requirements, and their need for capacity building. All costs and benefits would have to be reduced to a single index so alternatives can be compared.

This study uses publicly available data. The lack of access to a complete set of data makes it difficult to estimate costs and benefits. For practical application, Singapore officials could use the framework presented in this report and plug in their numbers. It will help them decide which water supply alternatives should be developed and the extent to which they should be used.

If I may, I would like to add that the Public Utilities Board (PUB), and Singaporeans in general, would benefit from more transparency. If more data were publicly available, it would allow experts, or scholars like me, to study the water situation of the island and give further recommendations to Singapore. In addition, sharing data with Malaysia would ensure that both countries reach water trading arrangements appropriate to each party. Also, despite the lack of transparency, it would not be surprising if Malaysia were well informed about Singapore's water situation. In any case, uncertainty always carries a cost and Malaysia is likely to cope with this uncertainty by asking for a price higher than what a fair price would be when re-negotiating its water agreements with Singapore.

Analysis

Institutional Framework and Performance of the Water Sector in Singapore

Securing access to water is a major concern for Singapore and the Public Utilities Board (PUB), the agency in charge of the management of the State's water resources, has been attacking the issue in a systematic, professional and efficient way[7]. The PUB was recently expanded with the integration of the Sewerage and Drainage Departments from the Ministry of the Environment (ENV) to become a comprehensive water authority[8]. The Board has now all the necessary competences to manage Singapore's water resources in an integrated way, including reservoirs, waterworks, rivers, drainage system, water reclamation plants and sewerage system. Thus, institutional and technical capacities are no limiting factors when implementing a national water policy. The following table gives key indicators of the PUB's performances.

Table 3. Performances of the Public Utilities Board of Singapore

Service Indicators	
Service Coverage	100%
Water Availability	24 hours/day
Per Capita Consumption	0.18 m^3/capita/day
Average Tariff	US$0.553/$m^3$
Drinking water	Boiled
Efficiency Indicators	
Unaccounted Water	6%
Non-Revenue Water	7%
Unit Production Cost	US$0.309/$m^3$
Operating Ratio	0.6
Accounts Receivable	1.1 months
Staff/1,000 Connections	2.95[c]

Source: ADB, 1997, p.169.

Notes: [a] Most consumers boil water before drinking as a matter of habit; of 18,654 water samples taken in 1995, 13 samples failed the bacteriological tests.
[b] Domestic meters are replaced once in 8 years while large meters are replaced once in 4 years.
[c] Derived from number of employees and number of accounts registered with PUB in 2002 (PUB Annual Report 2002, p.40)

High unaccounted for water (UFW) and non-revenue water rates are often the cause of huge wastage in developing countries, but this is not the case in Singapore. Both the UFW and non-revenue water rates, as well as the number of employees per 1,000 connections – a traditional criteria for efficiency - are low relative to worldwide averages,

[7] ADB, 1993.
[8] PUB Annual Report 2001. The integration took place on April 2001.

signs of a well managed agency. The efficiency and professionalism of PUB staff will facilitate the development of new water supplies for the State.

Projected Water Demand and Available Resources in Singapore

Water Supply

Rainwater harvesting is the main source of freshwater in Singapore. The total rain fall over the island is on average equal to 603 million m^3/year[9]. Deducting evaporation at the rate of 329 million m^3/year, the net amount of available freshwater in the island equals about 271 million m^3/year. Half of this volume is collected through catchment works. In addition, the PUB started drainage works to isolate the Marina Channel from the sea[10], thus impounding the freshwater upstream. Thanks to this project, an additional 85 million m^3 of rainwater/year will be collected by the end of 2006 (assuming a rainfall volume over the Marina Channel equal to 195.6 million m^3/year minus the evaporation of 110 million m^3/year[11]).

Groundwater resources are very limited. A study undertaken in the late 1940s found that pumping water from the Bedok Valley could yield 3 million gallons per day (mgd - 13,600 m^3/day)[12], equivalent to 4.96 million m^3/year.

Adding the freshwater resources listed above, Singapore currently disposes of a total of about 186 million m^3 of freshwater per year, and will increase this catchment to 243 million m^3/year by 2012.

[9] Yap, 1994/95.
[10] PUB Annual Report 2002.
[11] Yap, 1994/95, p. 47.
[12] White, B. (1952) "The Water Resources of Singapore Island. Report on the Development of the City of Singapore of Singapore Water Supply and Emergency Supplies in Relation Thereto", Singapore. Cited in Yap, 1994/95, p. 14.

Water Demand

Current and projected water demand for 2011[13] are summarized in Table 4. Two methods were used to estimate these demands: (1) based on population growth and per capita consumption, and (2) based on water sales. Details are given in Appendix III. Both methods present some caveats and give imperfect estimates of water demand. Future population growth rate depends on government's policy, economic growth rate, and other events. Plus, in the case of Singapore, the total population counts a large share (about 20% in 2004[14]) of transient population. Both transient and permanent residents contribute to water demand and should be taken into account. The differences in water demand from both population types and variability of future trends lead to further uncertainties in population projections. Besides, water demand might not increase to the levels given in Table 4 thanks to technological progress and to financial and regulatory incentives applied to encourage water savings. Projections of water demand would need to be refined to better address Singapore's water situation. The subsequent sections deal with water supply alternatives available to meet these needs.

Table 4. Estimated Current and Projected Water Demand in Singapore (million m^3/year)*

	2004	2011
Maximum	531.69	693.71
Minimum	335.20	352.40

* Details of the analysis are given in Appendix III.

[13] Note that this study does not address the situation at the expiration date of the 1962 agreement with the State of Johor (expires in 2061) as planning for 57 years from now is not realistically feasible.
[14] <http://www.sg/snapshot/snap_land.asp>.

Negotiations of Water Trade with the State of Johor

Water transactions between Singapore and Malaysia date as far back as 1927 (see Table 5). Since then, three agreements were signed in 1961, 1962, and 1990 by the PUB and the State of Johor in Malaysia, and are still in force.

Table 5. Agreements governing Singapore-Malaysia water trading

Signature Date	*Agreement and its content*
1927	Agreement signed between the Singapore City Council and the Sultan of Johor which allows Singapore to draw water from Sungei Pulai free of charge. Agreement abrogated in 1961.(1)
1961	Agreement with Johor which gives Singapore the right to extract 86 mgd (equivalent to 0.4 million cubic meters) from the Pontian and Gunung Pulai Reservoirs, as well as the Tebrau and Skudai Rivers(3). This contract expires in 2011.
1962	Agreement with Johor which gives Singapore the right to extract 250 mgd (equivalent to 1.15 million cubic meters) from the Johor River(3). This contract expires in 2061
1990	Agreement which allows Singapore to dam the Sungei Linggui river and to draw additional water in excess of the present entitlement of 250 mgd from the Johor River.(2) The cost of additional water is the maximum cost calculated by these following two formulas: (1) half the difference between the price of water sold in Singapore and the price paid, less operating, distribution and management costs; (2) 115% of the price the Johor State charges its population for water.(4) This contract expires in 2061.
2001	Tentative agreement between Senior Minister Lee and Prime Minister Mahathir which *"looked to have provided some renewed assurance that Malaysia would continue to provide water to Singapore to meet its domestic and industrial needs – at least for the short to medium term. In return, Singapore had offered to pay 15 times more for the water than it currently pays."*(3)

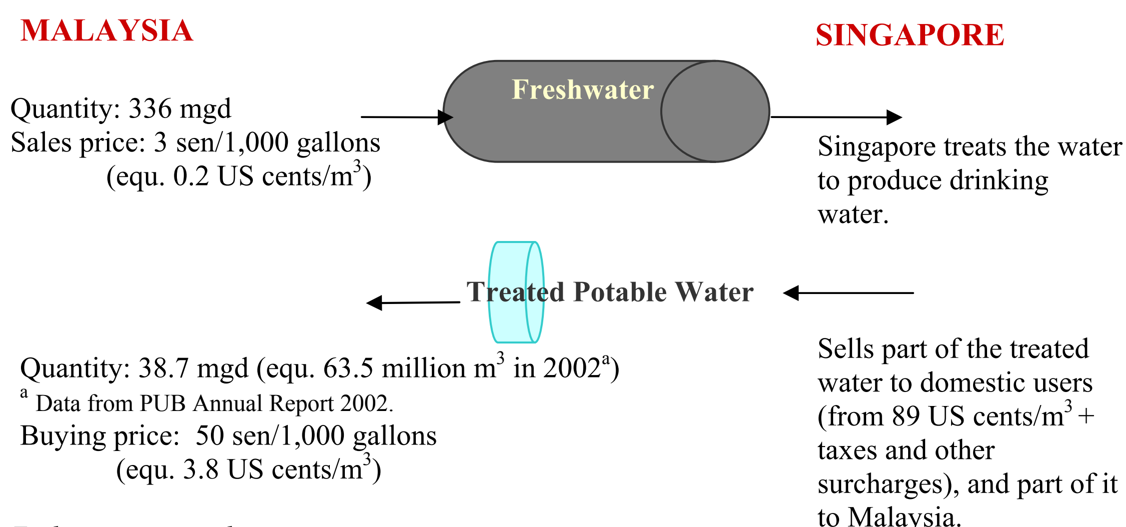
(1) *Business Times*, 29-30 Jun 1991.
(2) IDSS, 2002, p. 6 & 32.
(3) *Ibid*, p. 52.
(4) *Strait Times*, 25 Nov 1990, "New pact will benefit Johor and reduce sensitivities, says Muhyiddin".

The 1961 and 1962 agreements combined allow Singapore to buy up to 336mgd (equivalent to 1.55 million cubic meters per day)[15], with 86mgd (0.39 million m^3) being secured under the 1961 agreement and 250mgd (1.15 million m^3/day) under the 1962

[15] IDSS, 2002, p. 52.

agreement. In addition, a 1990 agreement included the construction of dams on the Sungei Linggui river and allowed Singapore to withdraw additional water supply[16]. Singapore buys the untreated freshwater from Malaysia, transferred via water pipes, and sells some of it back to Malaysia as treated potable water. Although Malaysia has a right to buy up to 15mgd, it buys about 37mgd of treated water[17]. This excess trading is informally agreed between the parties. Prices for each transactions were set by the agreements at 3 Malaysian Sen (equivalent to 1.4 Singapore cents or 0.8 US cent) per 1,000 gallons raw water bought by Singapore from Malaysia, and 50 Malaysian Sen per 1,000 gallons of drinking water sold back to Malaysia[18].

Figure 1. Water Trading between Singapore and Malaysia[19]



Exchange rates used:
1 Singapore dollar = 100 Singapore cent
1 Malaysian Ringgit = 100 Malaysian sens
1 Malaysian sen = 0.47 Singapore cent
1 Singapore dollar = 0.6 US dollar

[16] *Ibid*, p.6.
[17] "S'pore Sells Subsidised Water to Johor" in *The Sunday Times*, 6 Sep 1998.
[18] Foreign Ministry of Malaysia, "Water: The Singapore-Malaysia Dispute - The Facts: Is a fair price for water too much to ask?", -- <http://domino.kln.gov.my>
[19] Since Singapore's independence, both countries use different currencies. However, payments to Johor continue to be in made in Malaysian Ringgit. These past years the Singapore dollar has appreciated against the Malaysian Ringgit, reducing the price of water that Singapore purchases from Johor and decreasing its revenue from sales of treated water to Johor (Yap, 1994/95, p. 70).

The renewal of these agreements is uncertain (see Box 2), opposed by the Malaysian government for the following reasons:

(1) Because some states in Malaysia suffer from water shortages themselves, the Malaysian population feel that they should have priority over Singapore with regard to access to the water resources available in their country;

> *"In March 1990, water rationing was imposed in the northern regions of Johor while water flowed from reservoirs in Johor managed by the PUB to Singapore. Critics have pointed out that this implies that the Johor government seemed to put Singaporean needs before those of the state[20]."*

(2) Malaysia is uncertain about its own future water needs and, consequently, is unwilling to commit to give a fixed amount of water to Singapore;

(3) The government of Singapore and the State of Johor disagree over the water trading prices;

(4) Existing political tensions between the government of Singapore and Malaysia interfere with their water talks (as discussed later, plus see in Box 5 the list of ongoing disputes undermining the relationship between Singapore and Malaysia); and

(5) Ethnic tensions between the Chinese community in Singapore and the Malay from Malaysia[21] put further pressure on their respective governments to cut water supply to Singapore. The quote below illustrates this tension.

> *"A Malay Malaysian claimed that … Malay Malaysians feel there was a serious and co-ordinated effort to bring down the Mahathir government and to slow Malaysia's rapid movement towards achieving their Vision 2020[22]. If this is indeed the prevailing sentiment of the average Malay Malaysian, then it will be very difficult for Singapore to continue to rely on Malaysia for a supply of water when the existing water agreement expires in 2061."* (IDSS, 2002, p. 39)

Political tensions between the two States can be traced back to 1965 when Singapore took its independence (see Box 3 for a brief history of Singapore). Since then, water has been used as a bargaining tool. The government of Malaysia threatened to cut its water supply if Singapore's foreign policy were damaging to Malaysia (see quote from Tunku Abdul Rahman, Malaysian Prime Minister in Box 4) and, in fear that the

[20] "Johor MB to Critic: Water Project Not a Disadvantage to Malaysia" in *The Straits Times*, 10 Apr 1990.
[21] Malays from Malaysia feel that the Chinese from Singapore always try to harm them.
[22] "A Malaysian's View on Relations with Singapore" in *The Sunday Times*, 20 Feb 2000.

Box 2. Difficulties Faced by Water Talks between Singapore and Malaysia to Renew their Water Contracts

"Singapore officials have been meeting their countrerparts in Malaysia to discuss a new 100-year water agreement after 2061. Singapore officials have requested 350 million gallons a day of raw water and 400 million gallons a day of treated water to be supplied by Johor and Pahang to meet its projected demand of 950 million gallons a day for a population of seven million 60 years from now. This request for water beyond 2061 is, however, contingent on Malaysia satisfying its own needs first. The Malaysian officials are prepared to supply Singapore the present volume of 250 million gallons a day and have asked Singapore to source for water elsewhere, perhaps Indonesia, or to build desalination plants to meet its additional water demands. This is because Malaysia cannot commit itself to a quantum in view of the uncertainty of its own situation in 150 years' time. In addition, Johor's and Pahang's resources are earmarked for an inter-state water transfer following the 1998 water crisis in the Kland Valley."

Source: IDSS, 2002, p.38.

government of Malaysia puts its words into actions, Singapore started building armed forces (SAF— Singapore Armed Forces) to defend the water supply infrastructure if needed (see quote from Lee Kuan Yew, Singapore Prime Minister in Box 4), among other defense concerns.

Disputes have been ongoing between Singapore and Malaysia over the price of their water transactions. Malaysia asked to raise the price of freshwater to 60 sen per 1,000 gallons from 2011, with adjustments for inflation every five years[23]. The government feels that while Singapore agrees to revise the transaction prices, it is delaying the process in order to gain time and keep on making profit out of the cheap raw water bought from Malaysia. Meanwhile, the Singaporean government asserts that it is subsidizing the treatment of raw water to drinking water for Johor at up to RM29 million a year by selling it back at lower price than the incurred cost of treatment.

[23] Ng Boon Yian, "A Deal for the Future" in *Today,* 5 Sep 2001, p. 1, and Irene Ng, "Tough Talks, Then Progress on KL Pact" in *The Straits Times*, 5 Sep 2001, p. 1.

Box 3. Singapore's history and economy in a nutshell

In 1819, Sir Thomas Stamford Raffles (1781-1826), agent of the British East India Company, made a treaty with the Sultan of Johor allowing the British to buil a settlement on Singapore Island. Singapore soon became the leading British trading center in South-east Asia and it later became a naval base. Japanese forces seized the island in 1942, but British rule was restored in 1945.

In 1963, Singapore became part of the Federation of Malaysia, which also included Malaya and the territories of Sabah and Sarawak on Borneo. In 1965, Singapore broke away and became independent.

The People's Action Party (PAP) has ruled Singapore since 1959 until 1990, when he resigned and was succeeded by Goh Chok Tong. Under the PAP, the economy has expanded rapidly though some consider its rule rather dictatorial.

The World Bank classifies Singapore as a "high-income" economy. A skilled work force has created a fast fgrowing economy,m but the recession in 1997-98 was a setback. Trade and finance are leading activities. Manufactures include electronic products, machinery, scientific instrucments, textiles and ships. Singapore has a large oil refinery. Petroleum products and manufactures are the main exports.

Data source: Atlas of the World (2002) Tenth Edition, Oxford University Press, p. 25.

Box 4. Quotes illustrating political tensions between Singapore and Malaysia on the water issue

"If Singapore's foreign policy was prejudicial to Malaysia's interest, they [Malaysia] could always bring pressure to bear on them [Singapore] by threatening to turn off the water in Johore."

Tunku Abdul Rahman, Malaysia Prime Minister
Source: IDSS, 2002, p.4

"He [Mahathir] was direct and asked what we were building the SAF [Singapore Armed Forces] for. I replied equally directly that we feared that at some time or other there could be a random act of madness like cutting off our water supplied which they [the Malaysians] had publicly threatened whenever there were differences between us … In [the Separation] agreement, the Malaysian government had guaranteed our water supply. IF this was breached, we would go to the UN Security Council. If water shortage became urgent, in an emergency, we would have to go in, forcibly if need be, to repair damaged pipes and machinery to restore the water flow. I was putting my cards on the table. He denied that such precipitate action would happen. I said I believe that he would not do this, but we had to be prepared for al contingencies."

Lee Kuan Yew, Singapore Prime Minister
Source: *From Third World to First: The Singapore Story 1965-2000* (Singapore: *The Straits Times Press and Times Media Pte Ltd,* 2000), p. 276.

However, Singapore officials claim that the main issue is not about money but about Singapore's independence vis-à-vis Malaysia. As set by the agreements, price revisions were supposed to be done in 1986 and 1987, but at that time, neither Malaysia not Singapore asked for it. Singapore is concerned that if Malaysia asserts the right to change agreed prices at different times, it might be a precedent that will impact every agreements signed between the two States, including the Independence of Singapore Agreement, and might undermine the validity of these agreements.

> *"The two Water Agreements are no ordinary agreements. They are so vital that they were confirmed and guaranteed by both Governments in the 1965 Separation Agreement, also known as the Independence of Singapore Agreement. This was registered at the United Nations. Both countries have to honor the terms of the agreements and the guarantee in the Separation Agreement. Any breach of the Water Agreements must call into question the Separation Agreement and can undermine our very existence."* (Statement by Minister for Foreign Affairs, Prof. S. Jayakumar, in Parliament, 25th Jan 2003).

Malaysia has publicly announced its will to become independent from Singapore vis-à-vis its treated water supply. Along these lines, the Malaysian Cabinet approved a S$315-million project for the construction of Semanggar water treatment plant, located near Kota Tinggi in Johor, and Johor has cut down its purchase of treated water from Singapore since 1995[24]. But cutting imports of treated water from Singapore and using domestic firms instead to treat the river water would result in a significant increase in water tariffs in Johor, which would raise protestations among the population. A domestic water treatment company (SAJ Holdings) interviewed by *the New Straits Times* in 2002 was explaining that it would have to charge consumers 300 Malaysian cents per 1,000

[24] "KL Approves $318m Waterworks for Johor" in *The Straits Times*, 19 Aug 2000 - IDSS, 2002, p. 36 & 56.

gallons in order to "break even"[25]. In fact, in January 2001, Johor has started to raise its domestic water tariffs by up to 40%[26].

Malaysia has to balance the pros and cons of cutting its water trading with Singapore versus renewing the agreements. Stopping water trades would not only raise water tariffs in Johor, but it would also take away a source of revenue. Furthermore, Singaporean investments in Malaysia are significant enough[27] that Malaysia would try to preserve these links and avoid too much degradation in its relations with Singapore. Taking all these concerns into account, it seems unlikely that Malaysia would decide to suddenly cut all water supply to Singapore.

Box 5. Ongoing disputes between Malaysia and Singapore

- *"Dispute over the sovereignty of the island Pedra Branca;*
- *the rental Malaysia pays Singapore for the Royal Malaysia Navy's 72-hectare base, KD Malaya, at Woodlands;*
- *airspace arrangements for planes from the Singapore air force to fly over Malaysian airspace;*
- *the relocation of the Malayan Railway station from Tanjong Pagar to Upper Bukit Timah and the related relocation of the Customs, Immigration and Quanrantine (CIQ) stations;*
- *the right of Malaysian workers from Peninsular Malaysia to withdraw their compulsory savings in the Central Providence Fund (CPF) when they returned home upon completion of their work contracts in Singapore; and*
- *closure of the section of the Singapore stock market, the Central Limit Order Book (CLOB), which traded Malaysian shares after the 1997 financial crisis."*

Data source: IDSS, 2002, p.6-7.

In brief, major issues associated with water trading with Malaysia include the following: (1) Uncertainty with regard to Johor's willingness to supply water to Singapore after expiration of the 1961 and 1962 water agreements; (2) If it were willing to renew the

[25] The New Strait Times, March 2002.
[26] Joey Long Shi Ruey, 2002, "On the Singapore-Malaysia Water Issue".
[27] "Singapore's investment in Johor reached RM5.85 billion for 662 manufacturing projects during 1990-96", Chia Siow Yue, web reference.

agreements, at what price would Malaysia be interested to continue its water trading with Singapore?; And (3) how much water would Malaysia be ready to provide to Singapore? Answer to these questions depend on whether or not Malaysia has a real concern towards its ability to meet its future water needs, and what could be its alternatives sources of treated water other than from Singapore (i.e. develop domestic water treatment plants, import treated water from other neighbors) – The cost of alternative sources is likely to exceed the cost of importing drinking water from Singapore. Still, because of all these uncertainties, Singapore needs to reduce its vulnerability towards Malaysia by developing additional water supply.

Storage Capacity and Rainwater Collection

Since Singapore's independence, extensive work has been undertaken by the PUB to expand the storage capacity of existing reservoirs and construct new ones (see Table 6 for a list of reservoirs and their capacity and Appendix II for a map of the reservoirs and water treatment works). Nowadays, about half of Singapore's total land area is used for catchment purpose, meaning that a total of 181 million m^3 of rain is collected per year. Future plans to expand rainwater harvesting to two third of the island's area[28] will increase this capacity to 238 million m^3/year. Given the competing demands of residential, industrial and economic development on the available real estate, it will be difficult for Singapore to further expand its rainwater collection. Still, more storage could be achieved by using tall towers[29].

[28] PUB Annual Report 2001, p.3.
[29] Towers are used in the Middle East to store water (fact given in BGP-256, lecture of February 18, by Professor Henry Lee).

Table 6. Singapore's Reservoirs and Current Storage Capacity

Name	*Year Completed*	*Storage Capacity (million m³)*
Singapore		
MacRitchie	1894	4.2[a]
Lower Peirce	1912	2.8 [a]
Seletar	1935 (extended in 1969)	24.1 [b]
Upper Peirce	1974	27.8 [c]
Kranji/Pandan	1975	22.5 [d]
Western Catchment	1981	31.4 [e]
Bedok/Sungei Seletar	1984	23.2 [f]
Sub-Total (Singapore)		*142.0*
Malaysia		
Pontian/Gunong Pulai	1932	17.5 [a]
Linggui	1993	770.0 [h]
Sub-Total (Malaysia)		*787.5*
TOTAL		**929.5**

Table reproduced from Yap, 1994/95, p. 25.
Notes and sources:

[a] Water Department Annual Report 1957
[b] PUB Annual Report 1967
[c] PUB Annual Report 1974
[d] PUB Annual Report 1970, 1973.
[e] *Hansard*, 30 Aug. 1983, col. 109-110.
[f] Engineering New Report, "Computer magic aids Singapore's water search", 15 Mar. 1984.
[g] It was reported in Parliament in 1983 that between 1980-82 the capacities of the Upper Peirce and Seletar Reservoirs were enlarged by a total of 6×10^6 m^3. *Hansard*, 30 Aug. 1983, col. 109-110.
[h] PUB Annual Report 1993.

Wastewater Re-Use

Water reclamation and reuse

Wastewater can be treated to achieve medium to good quality water that can be reused. It has the advantage to free the available freshwater for potable use for example. Thanks to a well developed sewage and collection system, the PUB already achieves a high rate of water reclamation. Early 2000, industrial water represented about 2% of all water consumed in Singapore[30]. In 2002, 480 million m^3 of used water was treated. As a

[30] Kog Yue Choong (2001) "Natural Resource Management and Environmental Security in Southeast Asia: A Case Study of Clean Water Supplies in Singapore", in *Non-traditional Security Issues in Southeast* Asia, ed. Andrea T.H. and J.D. Kenneth Boutin, Singapore: Select Publishing for Institute of Defense and Strategic Studies, 2001. Cited in IDSS, 2002, p. 31.

reference for comparison, the annual drinking water sales was equal to 459.5 million m^3 (1.247 million m^3/day[31]) in 2002. PUB operates and maintains six water reclamation plants[32]. The total capacity of wastewater reuse was increased by 18.3 million m^3/year (50,000 m^3/day) in 2003 by upgrading one of the facility. Current work on the Jurong Water Reclamation Plant will further increase this potential reuse by 15 million m^3/year (41,000 m^3/day) by the end of 2004. The total capacity of water reclamation will be about 513.3 million m^3/year by the end of 2004. The total cost of expansion and upgrading of water reclamation facilities in 2002 was S$135 million. Treated wastewater is sold at much cheaper rate than treated freshwater, 43 Singaporean cents per cubic meter against a minimum charge of 117 Singaporean cents per cubic meter of freshwater. Plus, no taxes nor additional fee are charged for the use of industrial treated water. This gives a strong incentive to industries which do not need water of potable quality (i.e. shipyard and textile) to use reused water instead. It encourages that water allocation be appropriate to its use and leads to more economical usage of water.

NEWwater

Singapore has launched an initiative which consists in treating wastewater with advanced purification and membrane technologies to produce high quality water. Its quality exceeds drinking water standards of the World Health Organisation (WHO) and United States Environmental Agency (USEPA)[33]. Three factories are in operation with a total capacity of 20mgd (90,920m^3/day), one at

[31] PUB Annual Report 2002, p. 7.
[32] PUB Annual Report 2002, p. 12.
[33] *Ibid*, p. 13.

Bedok, one at Kranji, and a recently built plant at Seletar. The first, pilot plan, built (in the Bedok Sewage Treatment Works) cost S$10 million (about 6 million US$)[34] and has been operational since 2001. NEWater is used by wafer fabrication plants, industries and commercial buildings. Since 2003, the use of NEWater is slowly expanded to domestic water purpose by mixing it to reservoir water and letting it undergo a process of naturalization before it is treated to produce potable water. Coupled with large commercialization efforts and educational campaign (as is already in place), and as long as the cost of NEWater can be competitive, this technique seems promising. PUB plans to provide up to 2.5% of total daily water consumption with NEWater by 2011[35].

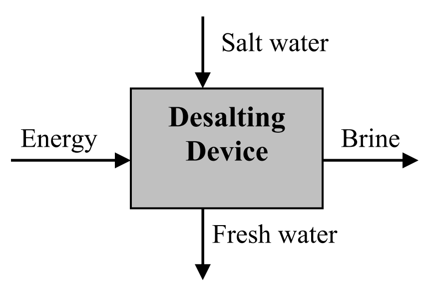
Desalination

Desalination refers to the removal of salts from seawater, brackish or treated waste water, to produce fresh water of drinking quality. As represented in Figure 2, the process needs energy and produces fresh water along with "brine", i.e. salt concentrate. There exist two main families of desalination techniques: thermal and membrane processes, described in Appendix IV. The choice of desalination technique is site specific and depends on the amount of treated water needed as well as on the economy or cost.

For prescriptive purpose, the choice of a desalination technique depends on the following parameters:

- Nature of the saline water, i.e. seawater versus brackish water: Reverse Osmosis

Figure 2. Schematic of a desalination process



Source: Reproduced from Buros (1998)

[34] IDSS, 2002, p. 42.
[35] PUB Annual Report 2002.

(RO) is more appropriate for seawater while electrodialysis and Multi-Stage Flash (MSF) distillation are best to desalting brackish water.

- Plant capacity: MSF units have the biggest capacity. Vapor compression plants are suitable for small-size projects.
- Capital cost and cost of O&M, which depends on the type of desalination plant and its design (i.e. cost of membranes vary, as well as the cost of heat exchanger in thermal systems), and on its maintenance requirement (i.e. control of scale formation).
- Energy efficiency: Multi-Effect Distillation (MED) plants has a high energy efficiency which makes them most appropriate when energy costs are high.
- Complexity of operation, in particular with respect to the control of scale formation.

The operation and maintenance of desalination plants require highly qualified staff, and spare parts often need to be imported. Because membranes can be easily clogged and damaged from suspended solids, the feedwater must be pre-treated before sending it to a RO plant. The water produced by desalination is generally pure and requires the addition of salts (i.e. carbon dioxide, limestone to adjust the pH of the water, hypochloride as a disinfectant for potability purpose) before distribution as drinking water, or for agricultural purpose. The brine is generally dumped in the sea, however, its high temperature might impact the local marine ecosystem.

The capital cost of a seawater RO unit could range from 800 to 1,250 US$/m^3/day of installed capacity[36]. The unit cost of desalinated water has been decreasing drastically

[36] UNEP (2000) "Sourcebook of Alternative Technologies for Freshwater Augumentation in Small Island Developing States", International Environmental Technology Center Technical Publication Series No. 8d.

this past decade. In fact, the RO desalination plant in construction in Singapore has the lowest estimated cost of 0.45 US$/$m^3$ when compared with the cost of other worldwide desalination plants (see Table 7). It remains essentially driven by the energy cost. To reduce operation cost, desalination techniques are developed in co-generation with power plants. This seems to be the case of the Singaporean plant. The use of hydropower, coal, or natural gas as the primary source of energy is less costly than using oil. Note however that natural gas should be preferred over coal for environmental purpose – coal being highly polluting. Solar and wind energy sources have been explored to run desalination plants such as reverse osmosis, electrodialysis, or distillation, but remain limited to small-scale apparatus.

When using RO systems, another cost-saving technique is to combine seawater with wastewater before sending it to the desalination plant[37]. This reduces the salinity of the feed water and, as a result, requires fewer membranes to reach potable water quality. This solution could be appropriate for Singapore as the collection of wastewater is already in place.

Two Singaporean universities are actively looking for ways to further reduce the cost of desalination[38]. This technology is already competitive relatively to bringing water through water tankers or pipelines and is promising in securing water supply. Even if Singapore does not end up relying on desalination for its daily water supply, it should keep this option as an emergency backup supply system. Storage could even be built to keep some desalinated water in reserve. Three desalination plants are already planned

[37] Khouri 1992. Cited in Dabbagh, Taysir, Peter Sadler, Abdulaziz Al-Saqabi, and Mohamed Sadeqi (1993) *In "Water in the Arab World: Perspectives and Prognosis",* ed. Peter Rogers and Peter Lydon, Harvard University Press: Cambridge, MA, pp. 203-241.

[38] IDSS, 2002, p. 42.

Table 7. Build-Own-Operate-Transfer Contract Costs for Desalination Projects

	Tampa Bay	Trinidad	Larnaca	Dhekelia	Singapore	Ashkelon	Algeirs
Design capacity (tons/day)	95,000	135,000	40,000	40,000	136,000	274,000	200,000
Developer	Poseidon	Ionics	IDE	Caramondani Desalination Plants Ltd	Hyflux	V.I.D. Desalination Company Ltd	Ionics
Feedwater	Power plant condenser discharge	Open water intake	Open water intake	Open water intake		Open water intake	
Seawater salinity (ppm)	26,000	38,000	40,000	40,000		40,000	40,000
Energy cost (US$/kWh)	0.04	0.04	0.057	0.053			
Contract term (year)	30	23	10	10	20	25	25
Contract year			2000	1996	2002	2002	2003
Contracted water price (US$/m^3)							
• Capital recovery	0.21		0.37	0.56		0.30	
• Non-capital components	0.25		0.43	0.53		0.22	
• Total-first year water price	0.46	0.71	0.80	1.09		0.52	
• Normalized water price for energy cost of US$0.04/kWh				1.02			
• Reduction in water price for energy cost of US$0.04/kWh			(0.07)	0.068			
• **Total first-year water price (US$/m^3)**	**0.46**	**0.71**	**0.73**	**1.09**	**0.45**	**0.52**	**0.82**

Source: Richard Morris, BRL Properties Inc., Private firm specialized in desalination, presentation on "Technological Trends in Desalination and Their Impact on Costs and the Environment" at The World Bank Waterweek 2004.

with a combined capacity high enough to replace the water supplied under Singapore's first water agreement with Malaysia[39]. The first one will be in operation by 2005 with a capacity of 136,000 cubic meters (30 million gallons) a day[40], the other two will be completed by 2011.

Developing Water Trade with Other Countries

One of Singapore's strategy has been to tie water supply agreements with joint development plans with its neighbors, in particular within the Singapore-Johor-Riau (SIJORI) growth triangle, thus creating inter-state interdependence[41]. Singapore and the Riau province of Indonesia signed on August 1990 an agreement *"on economic co-operation in the framework of the development of the Riau Province"*. It includes cooperation over issues like trade, tourism, investment, infra-structural and spatial development, banking, etc.[42]. Under this agreement, both countries agreed to *"cooperate on the sourcing, supply and distribution of water to Singapore"*. It was followed by a water agreement signed on 28 June 1991 with the Indonesia's Riau Province to provide for the development of Bintan's water resources[43] and the supply of up to 4.5 million m^3 of water per day to Singapore for one century, starting from 2005, via undersea pipelines[44]. Two joint ventures were specifically created to implement this agreement[45]. Appendix V shows the foreign sources of water currently available to Singapore, or under development.

[39] "3 Water Plants for Singapore by Year 2001" in *The Straits Times*, 4 May 1998.
[40] "New Plant Sells Potable Water" in *The Straits Times*, 3 Jan 2000.
[41] IDSS, 2002, p. 40
[42] Treaties Supplement No. 1, "Agreement between the Government of the Republic of Singapore and the Government of Indonesia on Economic Co-operation in the Framework of the Development of the Riau Province" in *Government Gazette*, 1990.
[43] Chia Siow Yue, web reference.
[44] Long, 2001.
[45] Yap, 1994/95, p. 27.

Similarly, Singapore plans on contracting water agreements with other water-rich neighbors such as West Sumatra[46], Papua New Guinea and Laos, from which water could be brought by large tankers[47].

Water supplied by neighboring countries can be transported via submarine pipelines, water tankers, or nylon fabric bags togged by tug. This later option is at its early stage of development and will not be discussed in this paper. However, it would cost much less than using water tankers and should be further looked into for future development.

Use of submarine pipelines

Submarine pipelines are costly and their repair, when needed, is difficult. Therefore, it is best to use them over no more than a few kilometers[48], to link proximate land masses or bigger islands with available water. Singapore is close enough to Bintan (50km, equivalent to 30 miles, afar) for submarine pipelines to be an appropriate mean of transport of water. In fact, subsequent to the 1990 agreement between these two regions, Singapore started building a 60km submarine pipeline to link the island to Bintan[49]. This project was undertaken by a PUB's subsidiary, Singapore Utilities International (SUI). The capital cost of pipeline projects depends on the length of the pipeline, material used, water depth, and sea-floor conditions. Their installation require highly specialized engineering firms. If water is sent to the pipeline by gravity, the operation is minimal. The maintenance consists in regularly inspecting the pipelines integrity, especially after storms.

---

[46] IDSS, 2002, p. 33.
[47] *Ibid*, p. 44.
[48] UNEP, 2000.
[49] Yap, 1994/95, p. 26. I could not find the costing of the pipeline project.

Use of water tankers

Using water tankers require loading and unloading facilities, operation which can be gravity-fed or activated through pumping, as well as water storage and distribution systems to the consumer[50]. The cost of this option is high, driven by the transportation cost. For reference, the cost of barging water from Dominica over distances of 100 km to 1,000 km varied from about $1.40/m3 to $5.70/m3 in the mid-1980s; The cost of transporting water from Puerto Rico to St. Thomas was $7.65/m3 in the early 1980s; And in 1996, Fiji budgeted $285,000 for emergency water supply by barging, which included the cost of trucking the water to and from the loading docks. These numbers indicate how much it would cost to barge water from Bintan to Singapore. Economy of scale can decrease the unit cost of transported water. The maintenance of water tankers consists of inspecting and cleaning the tankers regularly to avoid contamination of the water. Barging is a suitable option to provide water in an emergency situation, but can be unreliable as it depends on sea conditions.

Other Water Conservation and Protection Measures

Other possible water conservation and protection measures include (1) further reducing the UFW, (2) protecting the quality of existing freshwater resources, (3) setting a secondary water distribution system for "grey water", and (4) encouraging water saving in agriculture (i.e. phasing out of pig farming). Extensive drainage system has already been developed by PUB to collect polluted runoff before it enters water bodies and similarly with sewage system to collect effluents. At the same time, the capacity of

[50] UNEP, 2000.

wastewater treatment plants have been increased to be able to treat all collected polluted effluents.

Controlling Water Demand

Singapore has already embarked on a program to reduce water consumption and ensure that its population treat water as a scarce and valuable resource. This plan includes implementing public education and publicity programs on water conservation, and encouraging water recycling and the use of non-potable water, such as industrial water and seawater, where applicable, as a substitute for potable water[51]. It was put into effect through the use of

- education about ways to save water (i.e. repairing any leakage at home, reducing the volume of flush in water closets, turning off the water tap whenever the water is not in use) and persuasion,
- fiscal incentives such as tax rebates as an incentive to curb wastage, a water conservation tax based on the volume of water used, and fines as deterrence against the misuse of water[52]. *"The Economic Expansion Incentives Act (Chap. 86) was amended in 1984 to allow for a 50% investment allowance for industrial consumers to undertake projects that reduce their consumption of potable water"*[53].
- a water pricing system under which domestic users pay a higher unit cost for the consumption of water above $40m^3$/month[54],

[51] Alliance to Save Energy (2002) "Watergy. Taking advantage of Untapped Energy and Water Efficiency opportunities in Municipal Water Systems", Alliance to Save Energy & USAID, pp. 140.
[52] Long, 2001.
[53] IDSS, 2002, p.32
[54] PUB Annual Report 2002.

- and legislative and administrative controls including regular checks of water use by water auditors in industries as well as in households. In particular, the Water Pollution Control and Drainage Act, Trade Effluent Regulations, and the various codes of practice for surface runoff and sewerage ensure that all new developments comply with the required pollution control standards and the quality of the discharge into water courses[55].

Table 8. Water Tariffs in Singapore as at 31 December 2002

Tariff Category	Consumption Block (m^3 per month)	Tariff (Singaporean cents/m^3)	WCT[a] (% of tariff)	WBF[b] (Singaporean cents/m^3)
Domestic	1 to 40	117	30	30
	Above 40	140	45	30
Non-domestic	All units	117	30	60
Shipping	All units	192	30	--
Industrial Water	All units	43	--	--
Sanitary Applicance Fee: S$3 per chargeable fitting per month				

Source: Table reproduced from PUB Annual Report 2002, p. 42.
Notes: [a] Water Conservation Tax is a tax levied by the Government to reinforce the water conservation message.
[b] Waterborne Fee
[c] The Sanitary Appliance Fee and WBF are charged to offset the cost of treating wastewater and the maintenance and extension of the public sewerage system.

[55] IDSS, 2002, p. 31.

Recommendations and Conclusions

Singapore officials should define a strategy for each of the three following scenarios: (1) Malaysia is willing to renew its water trading with Singapore but wants to negotiate a higher price of supplied raw water; (2) Malaysia announces that it will not renew the 1961 water trading agreement, and (3) there is a risk that Malaysia decides to suddenly cut all or part of the water supply to Singapore. To assist Singaporean officials in their decision-making, the water situation of the country was estimated and several water supply alternatives presented. Table 9 summarizes the unit cost of these alternatives along with the amount of water currently, or planned to be, supplied to Singapore. A thorough comparison of the water supply alternatives would have to take into account capital costs as well. Unfortunately, these costs were not publicly available and could not be included in this study. Note also that the actual cost of water supplied from Johor is increased by the land rental fee of S$5 per acre per annum that Singapore pays for the land reserved for its waterworks. The same would probably apply to the supply from Riau. The current and future supply curves presented in Figures 3 and 4 were deducted from the quantities and unit costs from Table 9. The range of estimated water demand is bounded by dashed lines, going from about 300 to 500 million m^3/year in 2004 and from 350 to 700 million m^3/year in 2011. If these estimates are correct, both current and future water needs are largely met, even without the water supplied from Johor. I am puzzled by this conclusion and suspect that either my projections for water demand are underestimated or Singapore officials decided to become independent of Malaysia. The following discussion explores alternative strategies that Singapore could have taken and discusses its choice towards independence from Johor.

Since the water provided by Johor is by far the cheapest option, it is in Singapore's interest to keep on negotiating with Malaysia to renew the water agreements. When negotiating with Malaysia under scenario #1, the cost comparison of Table 9 can help set an upper bound on the price that Singapore would be willing to pay for Johor's water. Any price above the desalination cost minus treatment cost of Johor's water, i.e. 45-15 = 30US cents/m^3, would not be worth spending to get water from Johor; unless financing capital cost and/or finding land space to build new desalination plants in Singapore become an issue.

Table 9. Unit cost of various water supply alternatives and quantity currently supplied or to be supplied in Singapore

	Quantity Supplied (million m^3/year)		Unit Cost (US$/$m^3$)
	2004	2011	
(a) Supply from Johor (Malaysia)	557.5	195.2	0.15 in 2004 0.19 in 2011
(b) Supply from Riau (Indonesia)	--	1,642.5	--
(c) Industrial water reuse	513.3	513.3	0.26
(d) Traditional supply	135.5	237.7	0.31
(e) Desalination	--	49.8	0.45
TOTAL	*1,206.3*	*2,639.4*	

Data sources:

(a) Supply from Johor, Malaysia: 86mgd granted by the 1961 Agreement until 2011 and 120mgd granted by the 1962 Agreement until 2061. To be conservative, it is assumed in this table that the 1961 Agreement is not renewed after 2011. Unit cost in 2004 equal to 3 malaysian sen per 1,000 gallons + treatment cost of 240 Malaysian sen per 1,000 gallons (The Strait Times, "The Root of the Dispute"); in 2011, the sale price of freshwater from Johor was set equal to 60 malaysian sen as an upper renegotiated price.

(b) Supply from Riau, Indonesia: 4.5 million m^3 per day granted by the 1991 Agreement. Unit cost not known but was assumed to be about equal to the supply cost from Johor when graphing supply curves, Figure 4.

(c) Industrial water reuse: Quantity produced and unit cost given in PUB Annual Report 2002, p. 12 and 42. Unit cost assumed to equal the tariff charged for industrial water, assuming that the PUB does not subsidize the use of industrial water.

(d) Traditional supply includes rainwater collection. Estimated in 2004 as being equal to half of total rainfall (minus rainfall over the Marina Channel) since about half of Singapore's total land area is used for catchment purpose; and estimated in 2011 as being equal to two third of total rainfall including rainfall over the Marina Channel since the Mariana Barrage currently under construction should be completed by 2006 (PUB Annual Report 2002). Unit production cost given by ADB, 1997, p. 69. This cost should be updated to current and projected costs.

(e) Desalination: 30mgd of desalinated water will be available by the end of 2005 (PUB Annual Report 2002, p.7). Unit cost given by Richard Morris, BRL Properties Inc.

Figure 3. Estimated Current Water Supply Curve in Singapore

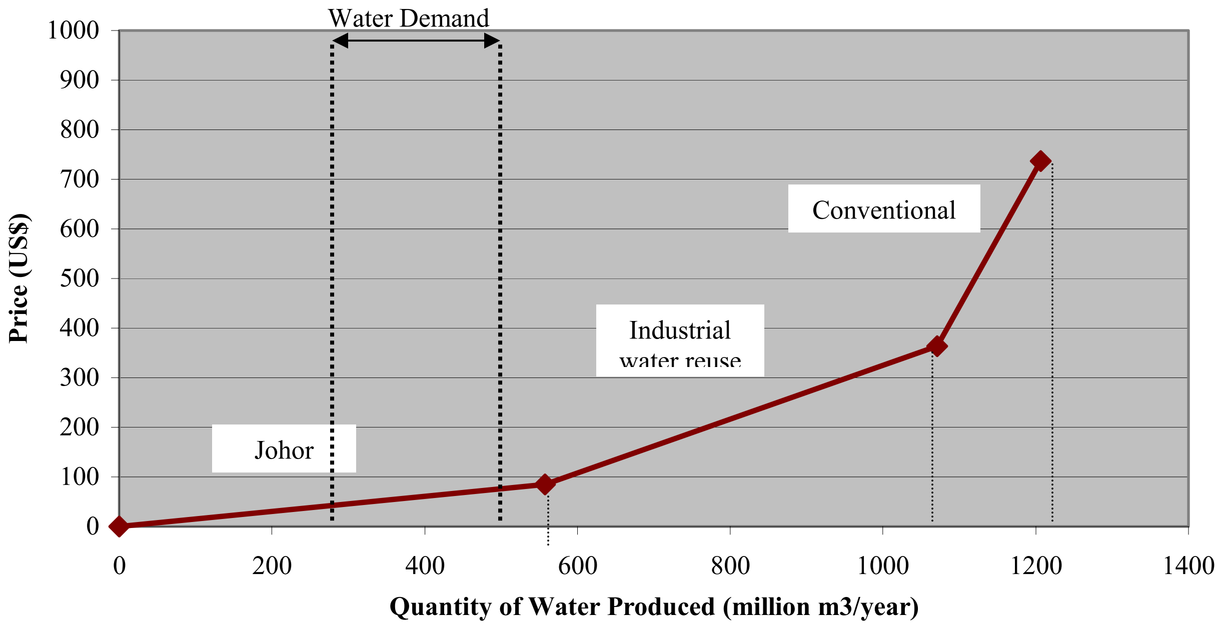
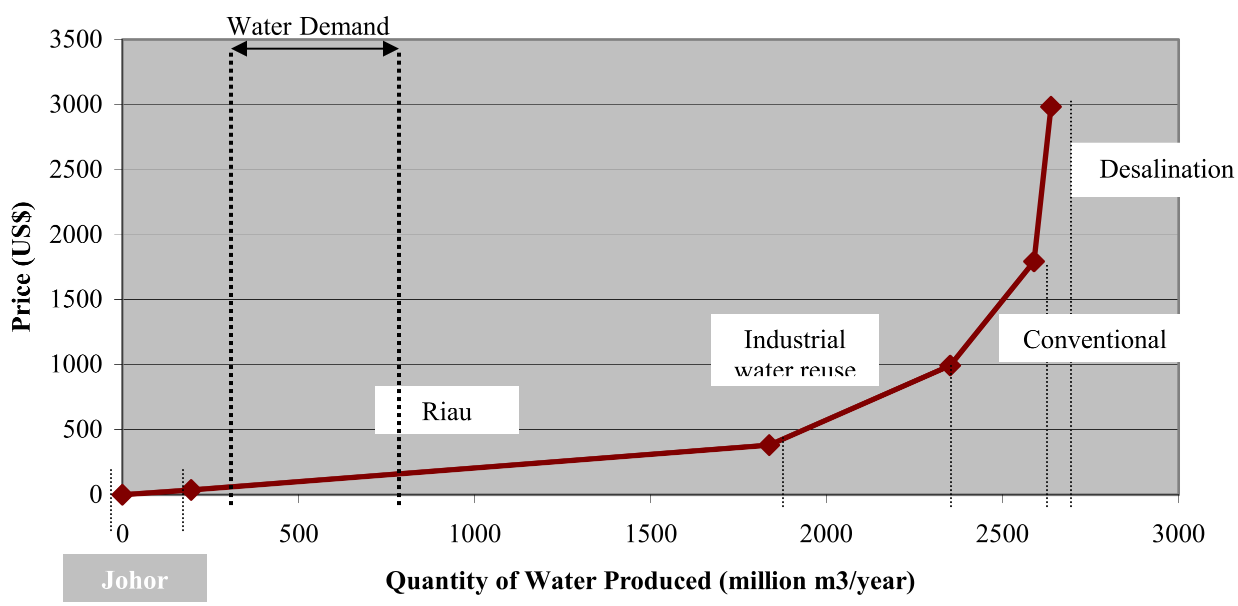


Figure 4. Estimated 2011 Water Supply Curve in Singapore



In case Malaysia announces that it will not renew one or both of the water trading agreements, whatever the water sale price be, Singapore can plan ahead of time how to meet its future water needs. Appropriate solutions include importing water from other neighbors such as Indonesia, building additional desalination plants, since desalination is among the cheapest options and the amount of seawater is non limiting, and continuing efforts to catch rainwater and reuse wastewater. The government of Singapore has already embarked on all of these options.

Possible strategies to cope with the third scenario of a sudden cut of water supply from Johor are: (1) to develop up-front enough water supply to end the trading with Johor – solutions which the PUB seems to be pursuing – , or (2) to maintain water trades with Johor but develop an emergency action plan that would be implemented in case of a cut. Which strategy would be best? The choice should be based on costs of each plan and depends on the probability of a water cut from Singapore.

A possible emergency plan could be as follow: (1) Build underground storage to store enough desalinated water produced from the plant that is currently under construction so Singapore water needs could be covered in an immediate time frame. Currently, Singapore's water resources can cover about four months of the current water consumption[56]. (2) Sign an agreement with Indonesia to have the right to import water in case of an emergency. This would cover the needs within a medium time frame. Since water imports would only be occasional, building pipelines between Singapore and Indonesia might not be economically justified. Water would be transported through water tankers. And (3) build an additional desalination plant that could be put in operation in case of an emergency, and which would reduce the need for imported water. It takes at

[56] Ibid *in IDSS, 2002, p.44*.

least five months to start a desalination plant so using plants left in stand-by would not cover immediate needs. Meanwhile, the use of diplomacy and military threat from Singapore against Malaysia, as well as the mobilization of the international community to put pressure on the Malaysian government to restore its water supply would help resolve the crisis. Several questions arise: Would Indonesia accept to provide water to Singapore only during hypothetical periods of crisis? And at what cost?

Cost of an emergency action plan

The cost of an emergency action plan depends on the probabilities of a cut, total or partial, from Malaysia. As an example, let's say that there is a 70% probability that Malaysia will not disrupt the water supply (trading links and political concerns are likely to dissuade Malaysia from taking drastic decisions against Singapore which explains this high probability of no cut), a 20% probability that it would cut half of its supply and a 10% probability of a total cut of water provision from Johor. Then, a rough and conservative estimate of the cost of Malaysian water equals 0.7×(cost of 336mgd imported from Johor + cost of other water supplies) + 0.2×(cost of barging 168mgd (half of 336mgd) of water from Indonesia the first months + cost of producing 168mgd of desalinated water afterwards + cost of other, non-Johor, water supplies) + 0.1×(cost of barging 336mgd of water from Indonesia the first months + cost of producing 336mgd of desalinated water afterwards + cost of other, non-Johor, water supplies). I am missing costings information to compute this cost.

Cost of full independence

Full independence, understood as the development of domestic water supply and trading agreement with Indonesia following the PUB's strategy, includes increasing water catchments, recycling water, transporting water from Indonesia through a sea pipeline and desalinating water. The total cost is estimated to be at least 2,600US$/year, the details of which are given in Table 10.

Table 10. Developing Singapore's independence from Johor's water supply

	Quantity Supplied (million m^3/year)	Unit Cost (US$/$m^3$)	Cumulative Cost (US$/year)
(b) Supply from Riau (Indonesia)	1,642.5	0.15*	250.09
(c) Industrial water reuse	513.3	0.26	811.90
(d) Traditional supply	237.7	0.31	1,551.49
(e) Desalination	49.8	0.45	2,650.97
TOTAL	*2,443.3*		*2,650.97*

Data sources: See sources listed for Table 9.
* The unit cost of water transported from Indonesia and treated to drinkable level is assumed here to equal the unit cost of drinkable water originating from Johor, however this is probably underestimated as the pipeline between Singapore and Riau will be longer than the one linking Singapore to Johor, thus increasing capital costs.

A comparison of the cost of an emergency plan and of developing full independence would tell which strategy is economically more desirable. The answer depends largely on the actual cost of water supplied from Indonesia. If Singapore can get water from Indonesia for a price as low as the water it gets from Johor, importing water from Indonesia is the best option. Otherwise, I would expect the emergency plan to be the cheapest. Yet, Singapore opted for full-independence vis-à-vis Johor. My guess is that this decision was driven by political reasons. It seems to me though that the stakes of deviating from the water agreements are too high for Malaysia to do so, as explained earlier. Singapore invests heavily in Malaysia and Johor gets 60% of Singapore's investment in Malaysia[57]. These trading links give bargaining power to Singapore in its water negotiations.

[57] Chia Siow Yue, web reference.

To conclude, my primary recommendation would be to diversify water supplies while staying engaged in water trading with Malaysia since this is their cheapest option. Achieving full independence vis-à-vis Malaysia might not be worth the cost. Singapore has the double advantage of being a buyer and a seller of cheap treated water for Malaysia which gives him additional weight in water negotiations, in addition to commercial interdependence between the two States. My second recommendation would be to continue current efforts in promoting water recycling, controlling water demand, and protecting the quality of Singapore's freshwater.

The framework developed in this paper could be applied to tackle other conflicts over water, while adapting to the specificities of these cases. Water disputes are recurring around the world, in the Middle East between Israel, Palestine, Jordan, Lebanon and Syria, in Africa, between Egypt, Ethiopia and Sudan which share the Nile River basin, in Central Asia between India and Bangladesh over water rights to the Ganges, and between India and Pakistan.

References

ADB (1993) “Water Utilities Data Book: Asian and Pacific Region”, *Asian Development Bank*: Manila.

ADB (1997) “Second Water Utilities Data Book for the Asian and Pacific Region”, Arthur C. McIntosh and Cesar E. Yniguez (eds.), *Asian Development Bank*, pp. 210.

Buros, O.K. (1998) “The ABCs of Desalting”, 2nd edition, *The International Desalination Association*, Topsfield: USA, pp. 32.

Chia Siow Yue, Director of Institute of Southeast Asian Studies, Singapore “THE INDONESIA-MALAYSIA-SINGAPORE GROWTH TRIANGLE”, Hong Kong Special Administrative Region of The People’s Republic of China – Government Information Center, <http://www.info.gov.hk/cpu/chinese/papers/c-sychia.rtf>.

IDSS (2002) “Beyond vulnerability? Water in Singapore-Malaysia Relations”, IDSS Monograph No. 3, includes papers by Kog Yue Choong, Irvin Lim Fang Jau, Joey Long Shi Ruey, and Kwa Chong Guan (ed.), IDSS: Singapore, pp. 154.

Long, Joey Shi Ruey, 2001, “Singapore, Malaysia and The Water Issue: A Concern Desecuritised”

The Straits Times - several articles.

UNEP (2000) “Sourcebook of Alternative Technologies for Freshwater Augumentation in Small Island Developing States”, International Environmental Technology Center Technical Publication Series No. 8d.

Yap, Adriel Lian Ho (1994/95) “Water for Singapore – Management of a Resource in a Subregional Economic Zone”, B.A. (Hons) Academic Exercise, Department of Geography, National University of Singapore, pp. 137

Appendices

Appendix I. Map of Singapore and surrounding, and its river system

See attached map

Appendix II. Reservoirs and Water Treatment Works in Singapore

See attached map

Appendix III. Projections of Water Demand in Singapore

Water Demand Based on Projections of Population Growth

Water demand data for Singapore are given in Table III.1.

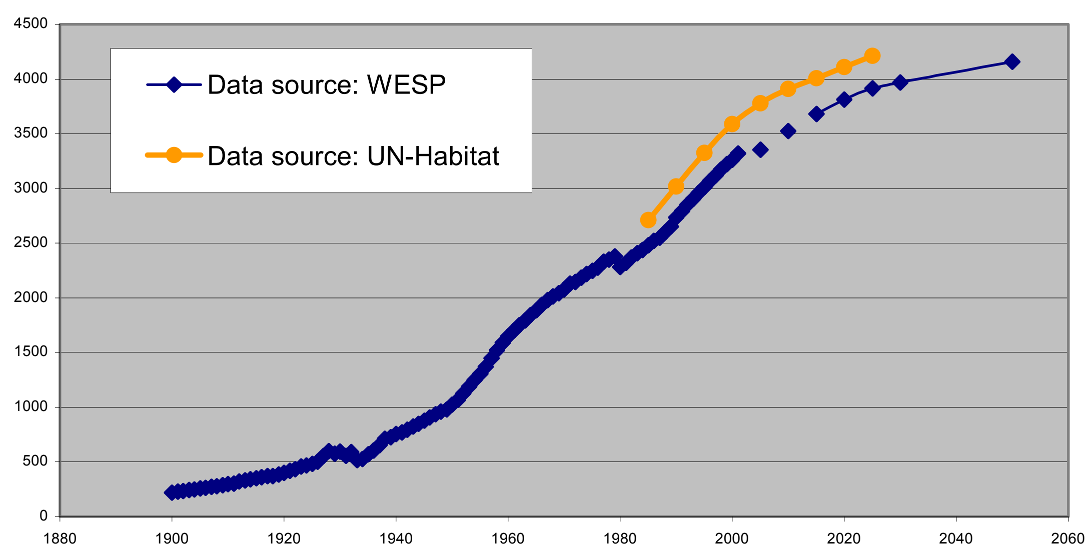
Table III.1. Water Demand in Singapore (in m^3/capita/year)

Year	1993	1994	1995	1996	1997
Water Demand	129	135	135	138	142
Year	1998	1999	2000	2001	2002
Water Demand	114	113	113	110	110

Data sources: PUB Annual Report 2002.
2002 consumption per capita is based on total population of Singapore as at 30/06/2002 of 4,163,700.
Consumption per capita prior to 1998 was based on resident population of Singapore.

Assuming that the water demand per capita will remain constant over time, **ranging from 100 to 130 m^3/capita/year**, future water demand can be approximated based on population growth. The population of Singapore is characterized by a large share (about 20% in 2004[58]) of transient population. Both transient and permanent residents or citizens contribute to water demand and should be taken into account. However, I suspect that the population data that I found only represents permanent residents or citizens. The reason is that according to the 2002 census, the population of Singapore in June 2002 was 4,163,700 people. Subsequently, population projections and future water demands will be underestimated. Plus, because different data sources give different numbers, we will consider a range of population growth to compute projected water demands.

Figure III.1. Population Trend in Singapore (in Thousand)



[58] Source: http://www.sg/snapshot/snap_land.asp.

Graphed population data come from the following sources:

1. **WESP** (updated on December 2003), “Population Statistics: Growth of the population per country in a historical perspective, including their administrative divisions and principal towns”, University Utrecht, The Netherlands, <http://www.library.uu.nl/wesp/populstat/Asia/singapoc.htm>. This website belongs to the Dutch "Werkgroep Seriële Publicaties" (WESP), in English: "Working Alliance on Serial Publications", in short: "WASP". The "WESP" was inaugurated on January 9, 1991 in Groningen, the Netherlands. It is part of a higher organization "UKB-CAT", that consists of chiefs of cataloguing departments mainly in university libraries of the Netherlands. The members of the "WESP" are library staff who are in charge of cataloguing serial publications, in university libraries, and other big libraries in the Netherlands that have large collections of serials (like the Royal Library and the Library of the Royal Netherlands Academy of Sciences).

Table III.2. Population Data from WESP (in Thousand)

population	*year*	***population***	*year*	***population***	*year*	***population***	*year*	***population***	***population***	*year*
								general total	residents	
	16XX	***220,0***	1900	***596,0***	1930	**1646,0**	1960	**3047,1**	**2735,9**	c1990
	17XX	**228,6**	c1901	**557,7**	c1931	**1702,0**	1961	**3135,8**	**2795,4**	1991m
	17XX	***236,0***	1902	**588,2**	1932	**1750,0**	1962	**3232,1**	**2851,1**	1992m
	180X	***243,0***	1903	***515,0***	1933	**1795,0**	1963	**3315,4**	**2906,5**	1993m
	180X	***250,0***	1904	***525,0***	1934	**1842,0**	1964	**3421,1**	**2961,4**	1994m
	181X	***257,0***	1905	***572,0***	1935	**1887,0**	1965	**3525,6**	**3014,6**	1995
	181X	***264,0***	1906	***603,0***	1936	**1934,0**	1966	**3670,4**	**3067,8**	1996
	182X	***271,0***	1907	***651,0***	1937	**1978,0**	1967	**3793,7**	**3121,1**	1997
	182X	***279,0***	1908	**710,0**	1938	**2012,0**	1968	**3922,0**	**3174,8**	1998
	183X	***287,0***	1909	**727,6**	1939	**2043,0**	1969	**3950,9**	**3221,9**	1999
	183X	***295,0***	1910	**755,0**	1940	**2074,5**	c1970	**4017,7**	**3262,2**	c2000
	183X	**303,3**	c1911	**769,2**	1941	**2129,0**	1971	**4131,2**	**3319,1**	*2001*
	184X	***321,0***	1912	***795,0***	1942	**2147,0**	1972			*2002*
	184X	**330,0**	1913	***822,0***	1943	**2185,0**	1973			*2003*
	184X	**339,4**	1914	***849,0***	1944	**2219,0**	1974			*2004*
	185X	**349,0**	1915	***878,0***	1945	**2250,0**	1975		***3352,0***	*2005ep*
	185X	**358,9**	1916	***907,0***	1946	**2278,0**	1976			*2006*
	185X	**369,2**	1917	**938,1**	c1947	**2330,0**	1977m			*2007*
	186X	**369,8**	1918	**961,0**	1948	**2350,0**	1978m			*2008*
	186X	**387,3**	1919	**979,0**	1949	**2380,0**	1979m			*2009*
	186X	**398,0**	1920	**1022,0**	1950	**2282,1**	c1980		***3524,0***	*2010ep*
97,1	1871	**418,4**	c1921	**1068,0**	1951	**2320,0**	1981m			*2011*
	187X	***436,0***	1922	**1127,0**	1952	**2370,0**	1982m			*2012*
	187X	***458,0***	1923	**1192,0**	1953	**2410,0**	1983m			*2013*
139,2	1881	***469,0***	1924	**1248,0**	1954	**2440,0**	1984m			*2014*
	188X	**485,1**	1925	**1306,0**	1955	**2480,0**	1985m		***3679,0***	*2015ep*

	188X	**502,0**	1926	**1372,0**	1956	**2520,0**	1986m			***3812,0***	*2020ep*
178,0	1890	**555,0**	1927	**1445,9**	c1957	**2550,0**	1987m	***4231,0***		***3914,0***	*2025ep*
182,7	1891	**599,3**	1928	**1519,0**	1958	**2600,0**	1988m			***3971,0***	*2030ep*
200,0	1895	***575,0***	1929	**1587,0**	1959	**2650,0**	1989m			***4161,0***	*2050ep*

'c' means census data; 'e' means estimate; 'm' means mid-year; 'p' means prognoses.
The figures in italic prior to 1950 are based on source "A hundred year (1890-1990) database for integrated environmental assessments", C.G.M. Klein Goldewijk and J.J. Battjes (1997). Source 1977-1994: " Key indicators Asian Pacific countries (1993, 1995)", v. 26(1995). Source from 1990 onwards: "Yearbook of statistics Singapore", ed. 2002 (ISSN 0583-3655).

2. **UN-Habitat** – United Nations Human Settlements Program, data downloaded from <http://www.unhabitat.org/habrdd/conditions/soeastasia/singapore.html>

Table III.3. Population Data from UN-Habitat (in Thousand)

Year	1985	1990	1995	2000	2005	2010	2015	2020	2025
Population	2,709	3,016	3,327	3,587	3,778	3,912	4,009	4,111	4,212

Population growth rates were computed from exponential regressions of each data set and are given in Table III.4. Based on water demand per capita (ranging from 70 to 120 m^3/capita/year) and estimated population, projected water demands are as follow:

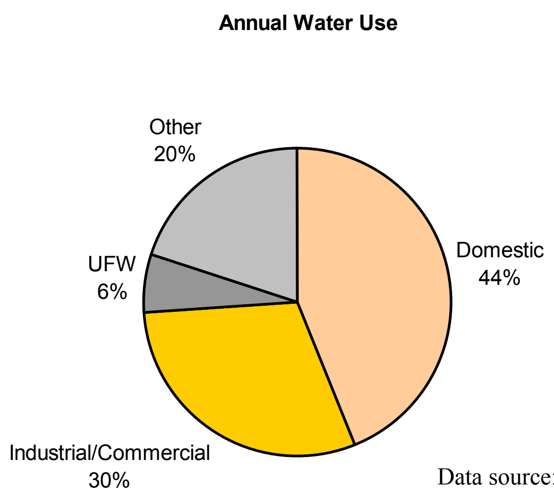
Table III.4. Projected Population Growth and Water Demand in Singapore

	Estimated Population Growth Rate (%)	**2004**		**2011**		**2061**	
Data Source		Population[a] (Thousand)	**Water Demand (million m^3/year)**	Population [b] (Thousand)	**Water Demand (million m^3/year)**	Population[c] (Thousand)	**Water Demand (million m^3/year)**
Maximum water demand -- using 130 m^3/capita/year							
WESP	0.8%	3,352	435.76	3,524	458.12	5,300	689.00
UN-Habitat	1.1%	3,778	**491.14**	3,912	**508.56**	6,800	**884.00**
Minimum water demand -- using 100 m^3/capita/year							
WESP	0.8%	3,352	**335.20**	3,524	**352,40**	5,300	**530.00**
UN-Habitat	1.1%	3,778	377.80	3,912	391.20	6,800	680.00

[a] 2005 data; [b] 2010 data; [c] Computed using exponential growth function and the estimated growth rate.

Water Demand Based on Projections of Water Sales

Future water demands are estimated here based on water sales data. About half of the water consumed is used for domestic purpose, the remaining being mainly used for industrial and commercial activities. Industries essentially include the manufacturing of machinery, chemicals, transport equipment, oil refining, electronics, food & rubber processing, biotechnology, and mining for granite. Agriculture represents only 1% of land use in Singapore, and a small percentage of the total water demand. Assuming that so far water supply was not limiting, and since the levels of unaccounted for water (UFW) and non-revenue water are very low in Singapore – 6% and 7% respectively[59] --, water sales can be used as an estimate of water demand.



Data source: Second Water Utilities Data Book for the Asian and Pacific Region, data as of 1995.

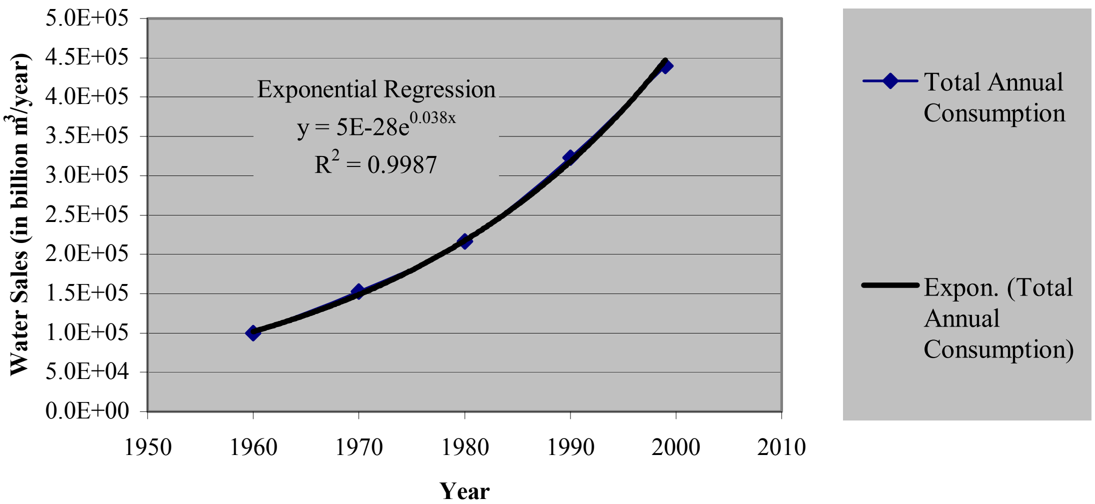
Table III.5. Water Sales in Singapore, 1960-1999 (in billion m^3)

Year	Domestic	Shipping	Commerce / Industry	Government	Total Annual Consumption
1960	40.79	n.a.	21.70	37.00	99.48
1970	71.02	2.28	35.72	43.92	152.94
1980	113.48	3.35	75.99	23.75	216.57
1990	177.34	2.91	113.15	29.39	322.80
1999	234.64	2.00	175.35	27.70	439.68
2004					***531.69***
2011					***693.71***
2061					***4,638.06***

Source: Department of Statistics, Singapore.
Numbers in italics were estimated using an exponential regression.

[59] McIntosh and Yniguez, 1997, p. 169.

Figure III.2. Total Annual Water Sales in Singapore

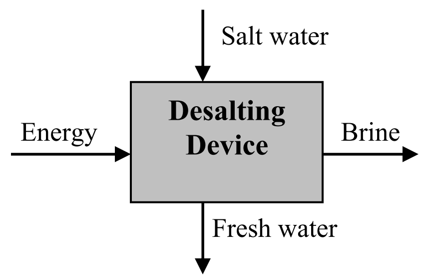


Estimations of water demand (or annual water sales) for 2004, 2011 and 2061 are higher than the estimated based on population growth. This can be explained by the fact that water sales include all economic sectors, i.e. shipping, in proportion of their water requirement instead of assuming a fixed water use per capita across sectors. These projections can serve as an upper-benchmark for future water demand. To refine water demand estimates, one would need to break up the water demand by sector of activity, i.e. domestic, government, hotels/restaurants, various types of industry, etc., and to undertake a survey of their projected water requirements. Such survey is very difficult to do as consumers are not very responsive or do not accurately estimate their future water needs.

Appendix IV. Desalination Technologies

Desalination refers to the removal of salts from seawater, brackish or treated waste water, to produce fresh water of drinking quality. As represented in Figure 1, the process needs energy and produces fresh water along with "brine", i.e. salt concentrate. There exist two main families of desalination techniques: thermal and membrane processes, described below[60]. The choice of desalination technique depends on the site specific conditions, water capacity needed to be treated and economy or cost. Note that plant efficiency is determined by its amount of treated water produced per unit of power –Water/Power (W/P) ratio.

Figure II.1. Schematic of a desalination process



Source: Reproduced from Buros (1998)

Thermal Processes

Thermal processes use steam to boil the salt water and produce a distillate along with brine, or salt concentrate (Figure 1). The heat is generally produced in co-generation of power. Since the boiling point of water decreases as pressure decreases, one way to reduce the energy needed for vaporization (and consequently to reduce the cost of treatment) is to use multiple boiling points in successive vessels, each operating at a lower temperature and pressure. Thus, at each stage, an additional portion of the feed water gets vaporized at lower pressure and lower temperature. A major concern with thermal processes is the formation of scale along distillation tubes from carbonates and sulfates, abundant in seawater. It causes thermal and mechanical problems. Ways to limit the formation of scale can be to control the concentration level of saline water and the top temperature of the process (as salts dissolve better at higher temperatures), or to add chemicals that reduce scale precipitation. Various thermal processes have been developed.

- *Multi-stage flash (MSF) distillation plant*

The first step consists in heating up the saline water using steam. Steam is generated from steam turbines of power plants or from a boiler. This method owes its name from the "flashing" or exploding effect caused by the quick transfer of the heated saline water from an ambient pressured vessel to a lower pressured one. The saline water vaporizes by flashing and is condensed on tubes of heat exchangers that run through each stage. There is no need to add more heat after the first stage. The saline water is thus distillated

Box II.1. Desalination Processes*

Major Processes

nal

- Multi-Stage Flash (MSF) Distillation
- Multiple-Effect Distillation (MED)
- Vapor Compression (MVC or MED-TVC)

rane

- Electrodialysis (ED)
- Electrodialysis Reversal (EDR)
- Reverse Osmosis (RO)

Minor Processes

Freezing
Membrane Distillation
Solar Humidification

* Box based on Buros (1998)
Source: IDA

---

[60] The description of desalination techniques given in this paper is based on Buros (1998).

in a series of vessels, each vessel being maintained at a lower atmospheric pressure than the previous one. An MSF plant can typically be made of 15 to 25 stages. The more stages there are, the more feed water gets distilled, but the more complex is the operation of the plant and the higher is the capital cost. The thermal efficiency of the plant depends essentially on the difference between the temperature of the brine heater exit and the temperature in the last stage on the cold end of the plant. The higher the difference, the more thermal efficient it is. MSF usually operates at the top brine temperatures of 90-119^{o}C (194-230^{o}F). However, there is a trade off between using high temperature to increase efficiency and lowering it to control the formation of scale. MSF plants are relatively easy to operate, are more resistant to scaling than other thermal units, and can reach very high water treatment capacity. Typically, MSF plants are built in units of about 4,000 to 57,000 m^3/d (1 to 15mgd).

Box II.2. Bahrain's extensive use of MSF and RO

"*The first multi-stage flash (MSF) distillation plant was introduced in Bahrain in 1976. The total installed capacity of this plant was 22,730 m³ (5 mg) per day in 1981, which was 15% of the total demand of 154,000 m³ (34 mig) per day. The present installed capacity of desalination plants in Bahrain is 205,000 m³ (45 mg) per day, including 160,000 m³ (35 mg) of seawater distillation by MSF and 45,000 m³ (10 mg) of desalination of brackish groundwater by RO. A further 45,000 m³ per day of seawater desalination capacity by RO is under construction (Mussayab 1988).*"

Source: Buros, 1998.

- *Multi-effect distillation (MED) plant*

Traditionally, MED is used in the production of sugar and salt from sugar cane. Like MSF, heat is added at the first stage of the plant, and the water vapor produced at each stage is used to heat up the following vessel. However, instead of sending all the saline water in each vessel one by one, it is sprayed, or otherwise distributed among the various units, in a thin enough film so that the sprayed water can evaporates instantaneously. A typical plant counts 8 to 16 units, with a total capacity of 2,000 to 20,000 m^3/d (0.5 to 5mgd), lower than MSF plants. MED plants can operate at lower temperature, of about 70^{o}C (158^{o}F), than MSF plants do, thus reducing the formation of scale. This is achieved through increased heat exchange surface area though, meaning that the required plant size is significantly bigger. MED has high energy efficiency and is then most appropriate when energy costs are high. Capital costs are also lower than for MSF plants.

- *Low-temperature thermal vapor compression (LT-TVC)*

Vapor compression systems use saline water in two-fold, in a cycle: Saline water is sprayed onto heated tubes and transformed into vapor. The vapor is then compressed (and thus heated) and used, in turn, to heat the incoming saline water. At the same time, heat exchange between the vapor and sprayed water condenses the vapor to produce a distillate. The mechanical compressor is usually electrically or diesel driven. VC can be used by itself for small to medium-scale saline water desalting applications (from a few liters up to 3,000 m^3/d (0.8mgd)), or in combination with other processes such as MED for treating bigger capacities of water. Their energy consumption is about 7 to 12 kWh/m^3 (26 to 45 kWh/1,000 gal.).

Membrane Technologies

Membranes are used to differentiate and selectively separate salts and water. The two main membrane technologies are electrodialysis (ED) and reverse osmosis (RO).

- *Electrodialysis (ED)*

ED is a voltage-driven process and uses an electrical potential to move salts selectively through a membrane, leaving fresh water behind as product water. It is normally used to desalt brackish water for producing potable water for municipal use. ED depends on the following general principles:

- Most salts dissolved in water are ionic, either positively (cationic) or negatively (anionic) charges.
- When an electric current is carried through saline water, these ions migrate toward the electrodes with an opposite electric charge.
- Membranes allow the selective passage of either anions (i.e. chloride, carbonate) or cations (i.e. calcium, sodium). Thus, ED uses pairs of membranes, each pair including an anion- and a cation-selective membrane. These pairs are usually referred to "cells". The cell pair consists of two cells, one from which the ions migrated (the dilute cell for the product water) and the other in which the ions concentrate (the concentrate cell for the brine stream).

An ED unit typically consists of several hundreds of cells bound in parallel with electrodes. Feed water must be pre-treated before it passes through the cells, to prevent materials that could harm or clog the membranes from entering the membrane stack. The water is circulated through the stack with a low-pressure pump to overcome the resistance of the water as it goes through the narrow openings of the cells. Water must be post-treated before its use to remove gases such as hydrogen sulfide and to adjust its pH.

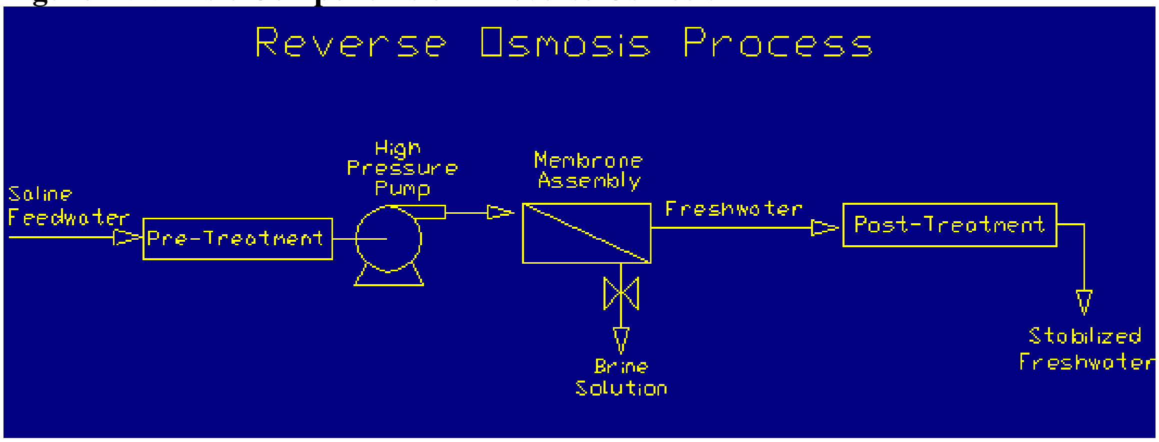
The electrodialysis reversal (EDR) process was developed on the same general principle as the standard ED, except that both the product and brine channels are identical in construction. At intervals of several times an hour, the polarity of the electrodes is reversed, and the flows are simultaneously switched so that the brine channel becomes the product water channel, and the product water channel becomes the brine channel. The reversal process allows the unit to operate with fewer pre-treatment chemicals and minimizes membrane fouling.

Advantages of the ED process include its high recovery capability (more product and less brine); the energy usage is proportional to the salts removed; ED can treat water with a higher level of suspended solids than RO; ED is unaffected by non-ionic substances such as silica; and has a low chemical usage for pre-treatment. The major energy requirement of ED is the direct current used to separate the ionic substances in the membrane stack.

- *Reverse osmosis (RO)*

RO is a pressure-driven process, with the pressure used for separation by allowing fresh water to move through a membrane, leaving the salts behind. Figure 4 gives a schematic of the RO process. Pre-treatment is important to ensure that membranes do not clog. Suspended solids must be removed, usually through fine filtration, and acid or other chemicals must be added to inhibit precipitation and microbial growth. The major energy requirement is for pressurizing the feed water through the membranes.

Figure II.1. Basic Components of a Reverse Osmosis



Reduction in the operating cost of RO could be achieved through the development of more efficient membranes (i.e. higher water flux, improved rejection of salts, lower prices, and longer lifetime), and the use of energy recovery devices. These later devices allow to reduce energy usage down to 3 kWh/m^3 (11.4 kWh/1,000 gal.) for seawater RO plants.

Other Processes

Other desalination processes such as freezing, membrane distillation, and solar humidification, have been developed but their use remains limited. They may prove valuable under special circumstances or with further development.

Freezing uses the fact that all dissolved salts are naturally excluded during the formation of ice crystals. The ice is then washed from the surrounding slats, and melted to produce fresh water. Freezing seems most appropriate for the treatment of industrial wastes than for the production of municipal drinking water.

Membrane distillation combines both the use of distillation and membranes. Saline water is vaporized first, the vapor is then filtered through a membrane (which can only let vapor pass through it) before being condensed on a cooler surface to produce fresh water. The main advantage of membrane distillation is its simplicity. However, because it uses a low temperature differential, its energy efficiency is very low.

Solar humidification was used on life rafts during World War II to produce drinking water from seawater. This process uses sun’s rays to evaporate the saline water, which is then condensed and collected as fresh water.

Appendix V. Foreign Sources of Water for Singapore

See attached map

This page is left blank intentionally.