Potential water resources in Singapore

Shu-Qing Yang

ABSTRACT

This paper presents guidelines on managing freshwater shortages on small islands and a case study on Singapore's water supply is discussed. By analysing Singapore's geographic conditions, it is found that abundant freshwater or brackish water is available in the mouth of the Johor River, which might function as one of the water resources to be developed since membrane technology drastically reduces the treatment cost of brackish water. A hydrodynamic model is applied for prediction of saline intrusion length and temporal distribution of salinity at the border of the Johor River after the proposed construction works are completed. Modelling results show that the oscillation zone of saline water intrusion in the Johor River mouth is in the range of 6 to 16.2 km, the equilibrium salinity is about 2.1 kg/m^3 and fresh/brackish water is available for 8 h daily at the border after the river mouth is partially closed.

Key words | equilibrium salinity, freshwater shortage, ocean reservoir, river mouth, seawater intrusion, water resources

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INTRODUCTION

Deltas at the mouths of rivers form the most productive areas in terms of agricultural production and fisheries resources, where the natural waterways are suitable for navigation and the relatively flat topography also offers the best potential for industrial development. These activities put stress on the quality and quantity aspects of water resources. Subsequently, small islands near the delta region undergo development. Despite their small area, some of these islands, for example Hong Kong and Singapore, have a very high population density and play very important roles in global economic activities and communication, which again puts great stress on water resources. In some island countries characterized by dense population, the water crisis, unlike the energy crisis, is the most important problem to resolve in becoming economically self-sufficient or politically independent.

Water on small islands occurs as freshwater, saline water and brackish water; the types of natural freshwater occurrence can be conveniently described under three headings: precipitation water, surface water and groundwater Falkland (1991). When climatic, geological and other conditions do not supply sufficient freshwater to meet the demand, it may be necessary to use artificial methods to provide the required freshwater, i.e. desalination or wastewater reuse. Another alternative to freshwater in small islands is importation, which is conceptually a simpler and viable solution if necessary.

In this paper we discuss Singapore's water supply. After a comprehensive review of current water resources, it is found that the development of fresh/brackish water in the Johor River mouth is the most viable option to solve Singapore's water crisis.

Singapore is a small tropical island between Malaysia and Indonesia, and lies off the southern tip of the Malay Peninsula between the lines of longitude E 103°38′ and 104°05′, and latitude N 1°09′ and 1°29′, as shown in Figure 1. Singapore was founded as a British trading colony in 1819. In 1963, Singapore joined Malaysia, but withdrew in 1965. It subsequently became an independent small island country and has the fifth highest per capita GDP in the world.

The climate of the Malay peninsula is humid and tropical. It is characterized by uniform temperature and pressure throughout the year. The mean temperature is

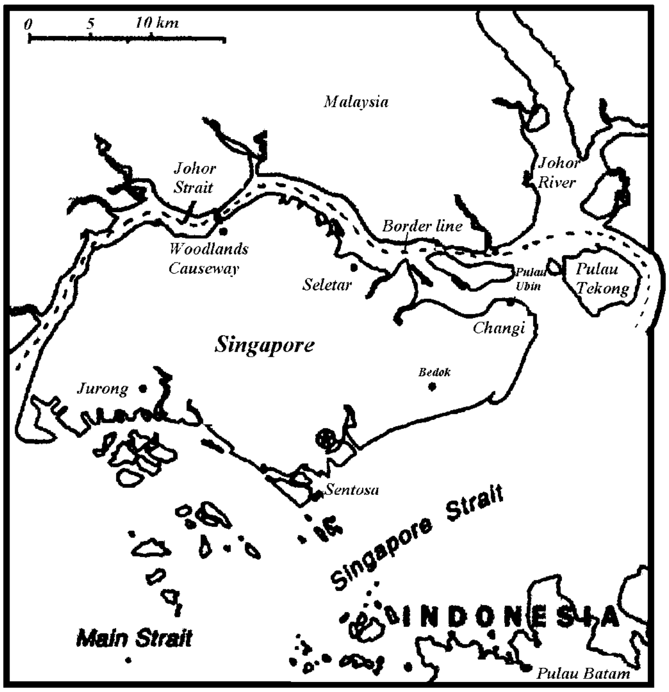

Figure 1 | Location map.

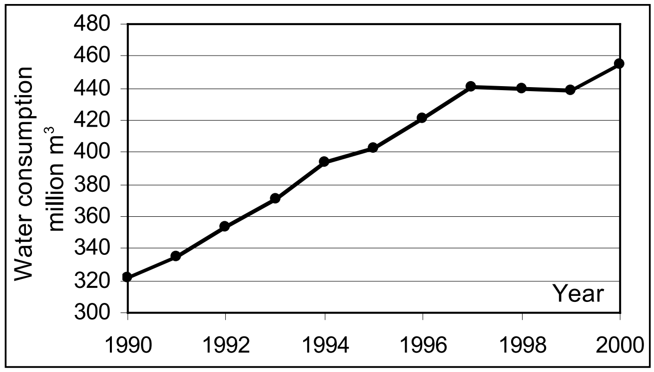

Figure 2 | Water consumption in Singapore from 1990 to 2000.

26.7°C. Although there is no distinct wet or dry season since rain falls during every month of the year, the climatic condition can be broadly divided into two monsoon periods associated with the prevailing monsoon winds. The south-west monsoon appears from May to September, and the wetter north-east monsoon from November to March in the following year. The mean annual rainfall recorded is 2.4 m. The highest annual rainfall recorded is 3 m and the lowest 1.5 m. The total evapotranspiration and infiltration loss is around 1.17 to 1.27 m per year. Table 1 shows the climatological data for Singapore.

REVIEW OF SINGAPORE'S CURRENT AND FUTURE WATER SUPPLY SCHEMES

In 2000, the total volume of water consumed in Singapore was 455.4 million m^3; the average increase in annual consumption from 1990 to 2000 was 3.5% due to the rapid economic and population growth. For the same period, Singapore's per capita consumption of water increased by an average of 0.5% per year, from 107 m^3 in 1990 to 113 m^3 in 2000 as shown in Figure 2.

Table 1 | Climatological data for Singapore

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Air temp. °C	25.5	26.1	26.5	27	27.3	27.4	27.2	27	26.9	26.7	26.2	25.7	26.7
Relative humidity	85	83.1	84.1	84.8	84.5	82.9	82.5	82.8	83.1	84.3	86.1	86.5	84.1
Sunshine h/day	5.03	6.34	6.11	5.93	5.9	6.09	6.21	5.97	5.58	5.2	4.65	4.51	5.63
Wind speed m/s	2.1	2	1.5	1.1	1.2	1.5	1.7	1.7	1.5	1.3	1.3	1.6	1.5
Rainfall mm	254	177	196	187	174	172	162	186	170	203	254	277	2,413

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Singapore's potable water is partially supplied from Malaysia across the Johor Strait through the Causeway, based on two agreements. However, the first agreement will expire in 2011, the second agreement in 2061. According to a new agreement in 2001, after 2061 Malaysia will only supply 1.575 million m^3 per day to Singapore, but 3.375 million m^3 per day are required according to the Singapore government. Therefore, Singapore's search for an alternative source of water has become a top priority. The water supply agreement between Singapore and Bintan, Indonesia, provides another source, but the study shows that it is costly in comparison with a desalination plant if the 450 km water supply pipelines are constructed.

Currently in Singapore, half of the island is used as a catchment to collect rainwater, however, 120 million m^3 of excess rainwater is discharged into the sea due to the shortage of inland reservoir capacity. The local water supply system comprises 19 raw water reservoirs, 9 treatment works, 14 storage or service reservoirs and a network of some 5,060 km of pipeline.

To augment water supply, Singapore has plans to further collect stormwater from residential towns as well as capture surface runoff from highly urbanized catchments. The catchment for rainwater collection will cover 75% of the island. Additional water supply schemes are desalination of seawater and recycling wastewater; 136,000 m^3 per day (30 mgd) of desalinated water plant will be established by the private desalination sector in 2005. A water treatment plant may generate 10,000 m^3 of water per day using membrane technology to recycle the wastewater. The treated water will be supplied to industrial users that require water for non-potable use. This will help to diversify the water sources and also meet the demand using potable water substitution. In addition, Singapore frequently conducts water conservation campaigns including economic measures. Figure 3 shows the price for water in Singapore over the last 10 years.

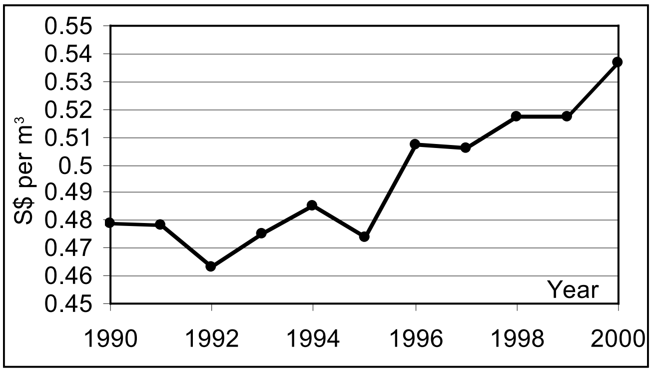

Figure 3 | Cost of water sold in Singapore from 1990 to 2000 (1US$=1.83S$).

WAYS OF MAXIMIZING THE USE OF FRESHWATER RESOURCES

In many parts of the globe there are insufficient available water resources to meet demand. To eliminate the water deficit, a solution has been suggested by UNESCO (1978) in three main directions:

(a) Saving water by reduction of specific water use.
(b) Regulation of river flow.
(c) Use of saltwater from the oceans or waste water.

To maximize the usage of available freshwater on the global scale, as river runoff to the oceans is 47,000 km^3 per year which is about half the total precipitation on land (119,000 km^3, UNESCO 1978), these additional guidelines are proposed:

1. Ocean reservoirs: to store the river runoff in ocean reservoirs near river mouths, solid or deformable ocean reservoirs are proposed by Yang (2002), by constructing barriers to separate the seawater and river water. Therefore, part of the river runoff to oceans may be stored in ocean reservoirs to alleviate the water stress.
2. To build weirs, sluice gates or inflatable rubber dams along a river course for bi-directional water conveyance. The excess rainwater flows to the ocean reservoirs after heavy downpours in wet periods, the pumping system may be operated to increase the river flow to the sea in order to mitigate floods if necessary, and the good quality water will be pumped and stored in the ocean reservoirs during this period.
3. In dry periods, the pumping system drives the fresh water from the ocean reservoirs to upstream

destinations along the river course to alleviate inland water stress.

4. To build a water diversion system along the shoreline to transfer the water from a full ocean reservoir to neighbouring ocean reservoirs which are short of freshwater. In other words, a coastal route for water diversion among different watersheds is suggested because of easier construction in coastal regions where the topography is relatively flat, and water demand is greater for denser populations relative to the upstream mountainous regions. The recent invention of water bag transportation on the ocean surface (Hsia & Hia 1997) is also recommended to transfer water among ocean reservoirs.

These suggestions may partially solve the water shortage problems for municipal water supply near the coast and on small islands. The application of the guidelines in Singapore will be outlined herein as a typical example.

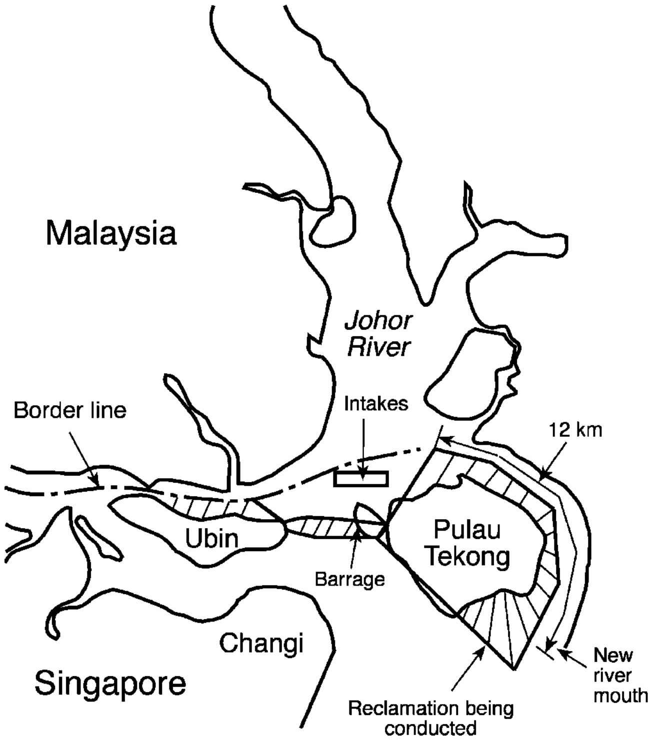

Figure 4 | Proposed partially closed ocean reservoir.

APPLYING THE GUIDELINES TO SOLVE FRESHWATER SHORTAGE PROBLEMS IN SINGAPORE

As shown in Figure 1, the largest river in Johor, Malaysia, carries abundant freshwater to Singapore territory, i.e. between Pulau Tekong and Pulau Ubin in Johor Strait. The watershed of the Johor River covers about 3,000 km^2. The Johor River can be considered an international river like the Nile or Mekong; in such cases upstream communities have a liability for downstream water supply and water quality, and downstream communities may utilise the water resource in the river mouth.

If Malaysia and Singapore both agreed to jointly develop the water resource in the river mouth, a fully closed reservoir could be easily built using a solid/soft dam (rubber inflatable dam) by connecting Pulau Ubin and Pulau Tekong with Malaysia, then both parties could share the reservoir. The interruption to navigation could be solved by using a ship lock located between Tekong and Ubin islands.

Due to this special case that the river and the river mouth belong to different countries, it is very difficult to reach an agreement for united development. Therefore, a partially closed reservoir is suggested, i.e. connecting Ubin and Tekong islands and narrowing the channels between Ubin, Tekong and Malaysia to reduce the seawater entering Johor River during a flood tide as shown in Figure 4. Reclamation is now being conducted for the purpose of extending the residential area of Singapore.

Hydrodynamic calculation of seawater intrusion into the Johor River

After the proposed construction works are completed, the intrusion volume of saltwater to the Johor River during a rising tide would be reduced as the possible saltwater intrusion would only exist in two channels on the north of Tekong and Ubin islands. If the river flow is large enough, the saltwater intrusion will go no further than the border, and freshwater or brackish water could be collected near the border.

Under normal river flow, the estimated water level variation, intrusion length of saline water and salinity variation near the border are presented below. The average width of the open channel connecting the partial closed reservoir and the sea is 600 m, the mean water depth, h, is about 6 m. The mean input freshwater discharge $Q_{up} = 110$ m^3/sec, while the peak discharge after a rainstorm with a re-occurrence period of 20 yr for the Johor River is 11,280 m^3/sec (Cheong *et al*. 1995).

Water level variation in the Johor River

The water level in the Johor River, Z_{up}, may be determined by the following mass conservation equation:

$$A\frac{dZ_{up}}{dt} = Q_{up} \mp Q_{down} \quad (1)$$

where A is the reservoir surface area, t is time and Q_{down} is the discharge from or to the sea. Q_{down} can be determined from the Manning equation if, in every time step, the flow is assumed to be quasi-steady.

$$Q_{down} = A_2 h^{2/3} S_1^{1/2}/n \quad (2)$$

where A_2 is the area of the channel cross-section ($A_2 = bh$), h is water depth, b is width of channel and n is the Manning coefficient. The values of b and h shown in Table 3 are obtained from the construction layout, the Manning coefficient n in excavated or dredged channels with an earth bottom and rubble sides is 0.03 (Chow 1973). The energy slope $S_1 = (Z_{up} - Z_{down})/L$ during an ebb tide where Z_{down} is the tidal level in the sea and L is the length of the channels connecting the reservoir and the sea. During a flood tide the energy slope will be determined by the following equation: $S_1 = (Z_{down} - Z_{up})/L$. Therefore, $Z^i_{up} = Z^{i-1}_{up} + V\Delta t$, where $V = (Q_{up} \pm Q_{down})/A$.

The computed results are shown in column 7 of Table 2. It can be seen that the water level variation in the Johor River is only 0.42 m while the sea level variation is 1.3 m.

Length of saline water intrusion and salinity variation at the border

For the Johor River, the ratio of incoming volume of freshwater to the seawater volume entering the river during the flood tide, N, can be determined using the values shown in Table 2. A value of $N = 0.17$ is obtained, according to Tuin (1991), showing that the Johor River will be a well-mixed river after the proposed construction works are undertaken. For a well-mixed estuary, studies on one-dimensional salinity intrusion have been conducted by many researchers, for example Ippen & Harleman (1961), Ippen (1966), Shinohara *et al*. (1969) and Furumoto & Awaya (1988). These models can generally provide sufficient accuracy for preliminary studies.

The governing equation developed by Ippen (1966) for the salinity at any distance x from the river mouth and any time t is used here:

$$\frac{S_{(x,t)}}{S_o} = \exp\{-\frac{u_f}{2D_0'B}[N_1 - (N_1 - x)e^{\frac{a_o}{h}(1-\cos\sigma t)} + B]^2\} \quad (3)$$

where $N_1 = hu_o/(a_o\sigma)$, u_o is maximum velocity at the ocean end, a_o is the tidal amplitude, σ is wave angular frequency, u_f is freshwater velocity, B is distance at low tide to maximum salinity from a river mouth, and D_o' is dispersion coefficient at a river mouth. The maximum intrusion of salinity occurs at high tide for $\sigma t = \pi$. Specifying the intrusion length by salinity of 1% of that in the ocean, the maximum intrusion length can be solved for $x = L_t$:

$$L_t = \frac{hu_o}{a_o\sigma}(1 - e^{\frac{2a_o}{h}}) + e^{\frac{2a_o}{h}} B(3\sqrt{\frac{D_O'}{u_f B}} - 1) \quad (4)$$

The minimum intrusion length L_l at low tide is:

$$L_1 = B(3\sqrt{\frac{D_O'}{u_f B}} - 1) \quad (5)$$

where $B \simeq u_o/\sigma(1\text{-}\cos\,\sigma t_B)$, where t_B = time interval from low tide to the arrival of the maximum salinity at $x = 0$, $D_o' = u_f B/(2\ln s_o/\overline{S}_{min})$, where $\overline{S}_{min}$ = the minimum average salinity at low tide at $x = 0$.

Two parameters need to be determined in Ippen's model, the minimum salinity $\overline{S}_{min}$ at low tide at the river mouth, and the time interval t_B from low tide to the arrival of the reference salinity S_o (= 30 kg/m^3) at the estuary

Table 2 | Salinity variation in the Johor River

Time (h)	Z_{down} (m)	Δt (h)	S (*10^{-5})	V (m/s)	Q_{down} (m^3/s)	Z_{up} (m)	Salinity (kg/m^3)
0:00	0.9	1	6.67	0.90	3,235	1.7	0.002
1:00	1.1	1	4.22	0.71	2,573	1.61	0.002
2:00	1.4	1	1.10	0.37	1,315	1.53	0.004
3:00	1.7	1	1.70	0.45	1,633	1.49	0.026
4:00	1.9	1	2.93	0.59	2,144	1.55	0.231
5:00	2	1	3.20	0.62	2,241	1.61	1.490
6:00	2	1	2.61	0.56	2,024	1.69	4.605
7:00	1.8	1	0.41	0.22	803	1.75	6.594
8:00	1.6	1	1.48	0.42	1,526	1.78	4.651
9:00	1.4	1	2.80	0.58	2,095	1.73	1.521
10:00	1.2	1	3.97	0.69	2,495	1.68	0.238
11:00	1.2	1	3.37	0.64	2,300	1.60	0.027
12:00	1.2	1	2.82	0.58	2,105	1.54	0.005
13:00	1.4	1	0.66	0.28	1,015	1.48	0.002
14:00	1.7	1	2.07	0.50	1,802	1.45	0.005
15:00	1.9	1	3.26	0.63	2,261	1.51	0.026
16:00	2.1	1	4.33	0.72	2,607	1.58	0.231
17:00	2.2	1	4.48	0.74	2,653	1.66	1.490
18:00	2.2	1	3.79	0.68	2,440	1.74	4.605
19:00	2	1	1.49	0.42	1,529	1.82	6.594
20:00	1.7	1	1.425	0.41	1,493	1.87	4.651
21:00	1.4	1	3.57	0.66	2,368	1.83	1.521
22:00	1.1	1	5.51	0.82	2,941	1.76	0.238
23:00	0.9	1	6.47	0.88	3,186	1.68	0.027

Table 3 | Hydraulic parameters used in the calculations

Parameter	Value
Manning's roughness n	0.03
Freshwater discharge Q_{up}	110 m^3/s
Flooding seawater volume	28.8 $m^3 \times 10^6$
Reservoir surface area A	80 km^2
Channel length L	12 km
Mean water depth h	6 m
Averaged channel width b	600 m
Tidal amplitude a_o	0.65 m
Maximum velocity u_o	0.9 m/s
Tidal wave period T	12 h
Time t_B	3 h
Distance B	6.2 km
Number N_1	5.7 km
Dispersion factor D_o'	84.6 m^2/s
Tidal angular frequency σ	1.45×10^{-4} s^{-1}
Maximum intrusion length L_t	16.2 km

entrance. In this estimation, $\overline{S}_{min}$ at $x=0$ is set to be 10 kg/m^3 and t_B is 3 h. Hume *et al*. (1995) obtained these values of t_B and $\overline{S}_{min}$ in Bahu Pahat River, which is similar to Johor River. The maximum velocity u_o in the channel can be determined from the Manning equation which is listed in Table 3. The amplitude of tidal wave a_o, and angular frequency σ are determined from the tidal level variation listed in column 2 of Table 2. The freshwater velocity u_f $(=Q_{up}/bh)$ is determined by freshwater discharge and cross-section area. Substituting, $\overline{S}_{min}$, S_o, a_o, σ, u_f and u_o into the expression of B and D_o', one gets $B=6.2$ km and $D_o'=84.65$ (m^2/sec). All the calculated parameters are listed in Table 3.

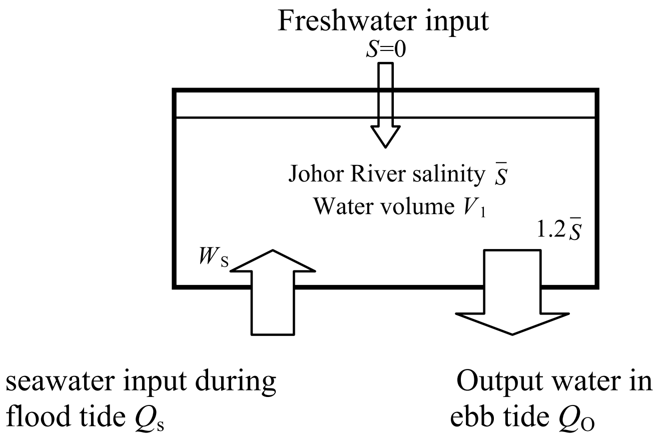

Figure 5 | Sketch of salt exchange in the Johor River mouth.

Substituting B, D_o' and u_f into Equation 5, one gets the minimum intrusion length at low tide $L_l=6$ km, and similarly the maximum intrusion length at high tide L_t can be determined. It should be mentioned that D_o' is sensitive to the estimated intrusion length, and this will be discussed in the following section.

The salinity variation at the proposed intake location ($x=16$ km upstream of the ocean) is estimated using Equation 3 and the results are shown in the last column of Table 2. It is obvious that the proposed intake may be in operation for 8 h daily, i.e. from 0:00 to 3:00 and from 11:00 to 14:00, for the salinity is very low when the river discharge is equal to or greater than 110 m^3/sec.

Equilibrium salinity in Johor River

In order to check the above predictions, especially the average salinity in the partially closed ocean reservoir, the equilibrium salinity in Johor River is calculated using a simple model shown in Figure 5.

The salt volume conservation equation is expressed as:

$$V_1\overline{S} + W_s\Delta t = V_1(\overline{S} + \Delta\overline{S}) + 1.2Q_o(\overline{S} + \Delta\overline{S})\Delta t \quad (6)$$

where V_1 = water volume in Johor River, $\overline{S}$ = mean salinity in Johor River, W_s = incoming salt rate from the sea, Q_o = outgoing discharge from Johor River. The salinity in

Table 4 | Comparison of hydraulic characteristics between Johor River and Chikugo River

River	River width (m)	River cross-section area (m^2)	Tidal range at river mouth (m)	Freshwater discharge (m^3/s)	Minimum salinity at river mouth (kg/m^3)	Minimum salinity intrusion length (km)	Maximum salinity intrusion length (km)
Chikugo	500	2,700	1.75~3.53	41~222	10 (measured)	9 (measured)	18 (measured)
Johor	600	3,600	1.30~3.00	110 (used for Eqn)	10 (estimated)	6 (from Eqn 5)	16.2 (from Eqn 4)

output water is slightly higher than the mean salinity, a ratio of 1.2 is assumed. One then gets:

$$\frac{d\bar{S}}{dt} = \frac{W_s - 1.2Q_o\bar{S}}{V_1} \tag{7}$$

With integration of the above equation with respect to time t with the initial condition $\bar{S} = S_o$ at $t = 0$, one gets:

$$\frac{\bar{S}}{S_o} = \frac{W_s}{1.2Q_oS_o} - \left(\frac{W_s}{1.2Q_oS_o} - 1\right)e^{\frac{1.2Q_ot}{V_1}} \tag{8}$$

where the daily incoming salt rate can be determined from Table 2 and $W_s = 2.1 \times 10^8$ kg/d, the daily outgoing discharge is estimated as mentioned above and $Q_o = 8.8 \times 10^7$ m^3/d, and the reservoir volume V_1 is evaluated to be 400 million m^3. It is estimated that the partially closed reservoir will take only one month to reduce the relative salinity $\bar{S}/S_o$ in Johor River to 10%.

It is obvious that when $t \rightarrow \infty$, the equation approaches the equilibrium salinity ratio:

$$\frac{\bar{S}}{S_o} = \frac{W_s}{1.2Q_oS_o} \tag{9}$$

The calculated equilibrium salinity in Johor River is about 2.0 kg/m^3 according to Equation 9. Comparing it with the average salinity of 1.6 kg/m^3 obtained from Equation 1, the difference is 0.5 kg/m^3, which indicates that Ippen's method (1966) slightly underestimates the salinity in Johor River. However, both predictions support the conclusion that fresh/brackish water is able to be collected at the proposed intakes after both islands are linked and reclamation works are completed.

The above conclusions may be similarly found in other field measurements. In Apalachicola River, Florida, USA, the measurement station is located about 25 km upstream of the river mouth. Huang & Spaulding (2000) measured the tidal water level that ranges about 0.8 m, which is similar to the partially closed reservoir. The hourly salinity was sampled at the station and they concluded that the clear water could be collected in the ebb tides when the upstream freshwater input is larger than 250 m^3/sec.

Batu Pahat River in Johor, Malaysia, may serve as a model of the proposed ocean reservoir: the catchment area and mean freshwater discharge are exactly half of Johor River. The criterion N (ratio of incoming volume of freshwater to the seawater volume entering the river during the flood tide) = 0.14, which is similar to that in Johor River. The distance between the two river mouths is about 130 km, the measured tidal variations are in the same ranges. The maximum length of seawater intrusion (L_t) is 32 km when the input freshwater flow is only 5 m^3/sec. The minimum length of saline water intrusion ($= L_1$) is 6 km when the river flow is 50 m^3/sec (Hume *et al.* 1995). The measured data set indicates that the estimations of seawater intrusion using Ippen's equation in Johor River are acceptable.

Chikugo River in Japan is comparable to Johor River in terms of river scale and tidal conditions as well as the freshwater discharge (see Table 4). The measured salinity intrusion lengths are in the range from 9 km to 18 km (Furumoto & Awaya 1988), which is similar to the estimation values in Johor River. This indicates that it is possible to draw the freshwater during particular periods at the proposed location 16 km upstream of the river mouth.

Proposed strategy for Singapore water supply

To eliminate the water deficit in Singapore, it is worthwhile to construct intakes in the Johor River mouth and to link Pulau Tekong and Pulau Ubin. The water collected from Johor River might serve as an alternative raw water source instead of used water/seawater in Singapore's current water strategy.

Since the ocean surface is very calm throughout the year in Singapore (see Table 1), it is an ideal place to build deformable ocean reservoirs (Yang 2002). Ocean reservoirs will become more important as population growth continues in this century because it is almost impossible for Singapore to expand further the capacity of reservoirs for rainwater storage. Singapore might save at least 120 million m^3 of excess rainwater annually from its catchment if the deformable ocean reservoirs are successfully developed.

As mentioned above, Singapore plans to build pipes on the seabed to deliver freshwater from Indonesia for occasional water supply. The new technology of water bag transportation on the ocean surface (Hsia & Hia 1997) may provide an alternative option. In cases of emergency, ships in the international port might tow the water bags from Indonesia to meet short-term demand. This would save the pipeline investment.

CONCLUSIONS

The proposed methods can be applied to Singapore and the water shortage that limits Singapore. Further development may be assisted by building a fully or partially closed reservoir in the Johor River mouth.

According to the hydrodynamic model, after the partially closed reservoir is built in the Johor River mouth, the water level variation in Johor River will be about 0.42 m. Saline intrusion oscillates up and down over a zone about 6–16.2 km long. The equilibrium means salinity in the Johor River will be 2.0 kg/m^3. The calculation results show that freshwater/brackish water could be collected at the proposed location during 8 h daily at the proposed location.

The measured results from rivers in Japan, USA and Malaysia show that freshwater/brackish water exists at 10 km upstream of a river mouth during the ebb tide. Hence, it is worthwhile to develop the water resources in the Johor River mouth for Singapore.

NOTATION

a_o	tidal amplitude
A	area of reservoir surface
A_2	area of the channel cross-section
B	distance at low tide to maximum salinity
b	width of channel
D'_o	dispersion coefficient at a river mouth
h	channel water depth
L	length of channel
L_l	minimum seawater intrusion
L_t	maximum seawater intrusion length
n	Manning coefficient
N	criterion for types of freshwater and seawater mixing in estuaries
N_1	$= hu_o/(a_o\sigma)$
Q_O	outgoing discharge from Johor River
Q_{down}	discharge from or to the sea
Q_{up}	river run-off discharge
S_1	energy slope $= (Z_{up} - Z_{down})/L$
$S_{(x,t)}$	salinity
S_o	seawater salinity
$\bar{S}_{min}$	minimum average salinity at river mouth
$\bar{S}$	mean salinity in Johor River
t	time
t_B	time interval at $x = 0$
u_o	maximum velocity at the ocean end
u_f	freshwater velocity
V	$= (Q_{up} \pm Q_{down})/A$
V_1	water volume in Johor River
W_s	incoming salt rate from the sea
x	distance
Z_{down}	tidal level in the sea
Z_{up}	water level in ocean reservoir
σ	wave angular frequency

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