Salinity in Lake Kinneret (the Sea of Galilee) – Its History, Environmental Challenges, and Management

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Israel Oceanographic & Limnological Research


Lake Kinneret
….Standing atop the Mount of Beatitudes and observing the landscape at its feet, it becomes clear why it was here, and not anywhere else, that Christ gave his famed sermon……
Mount of Beautitud - Dubi Tal and Moni Haramati

Lake Kinneret salinity in peer reviewed journals- special example

Journal of Paleolimnology (2006) 35:417–439
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Is there a paleolimnological explanation for 'walking on water' of Galilee?

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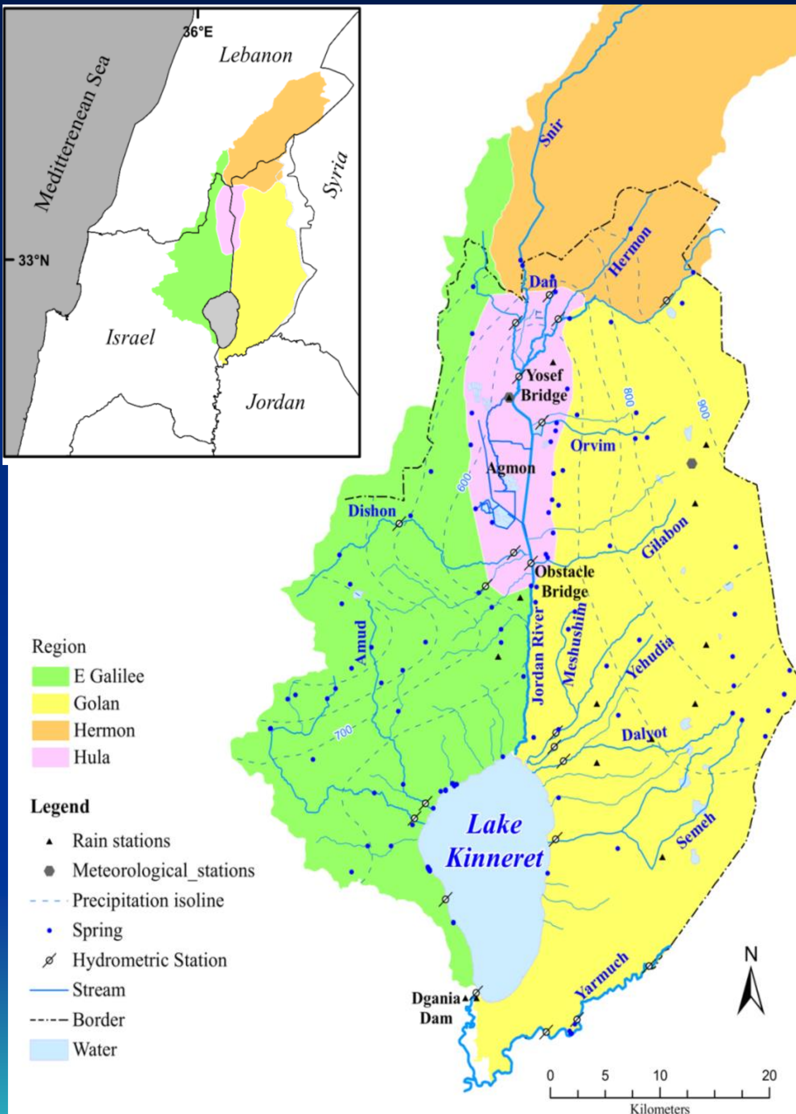
Key words: 'Walking on water', Air–lake interaction, Convection, Lake freezing, Salty springs

Lake Kinneret, Sea of Galilee, Israel



- The most important surface water resource in Israel,
- Lake Kinneret provides approximately 35% of the annual drinking water, through the National Water Carrier (NWC).
- The area of the Lake Kinneret Watershed is ~2730 km^2, where ~2000 km^2 are in Israel, and the rest of the area is in Syria and Lebanon.
- The average area of the LK surface is 166 km^2, the average volume is 4,100 Mm^3, the average annual available water is ~470 Mm^3, and the average residence time is ~8.3 years.

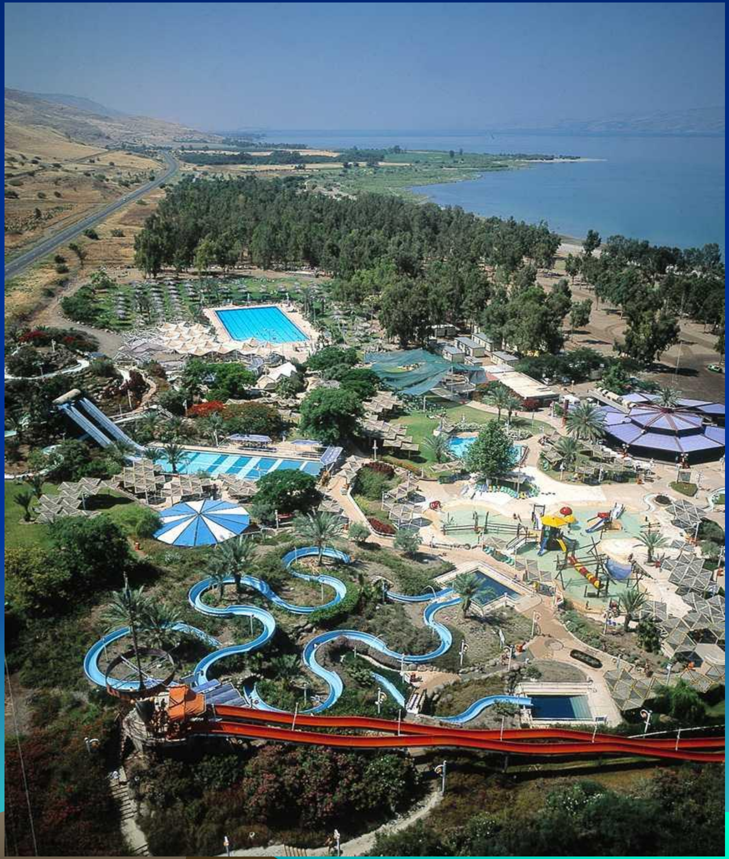
m^3 = 0.000810713 ac*ft ; Mm^3 = 810.713 ac*ft ; 470 Mm^3 = 381,035.11 ac*ft ; About 0.25 of the CAP

Lake Kinneret usages

Fishing

Water supply

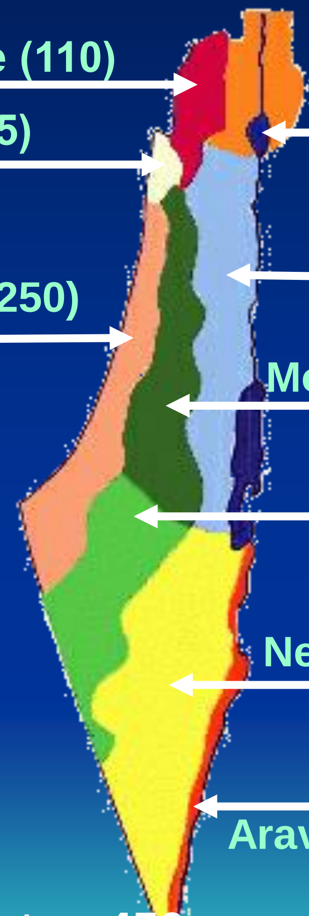
Recreation and tourist attraction



Lake Kinneret Level

The natural water sources of Israel

Annual averages [million m^3]



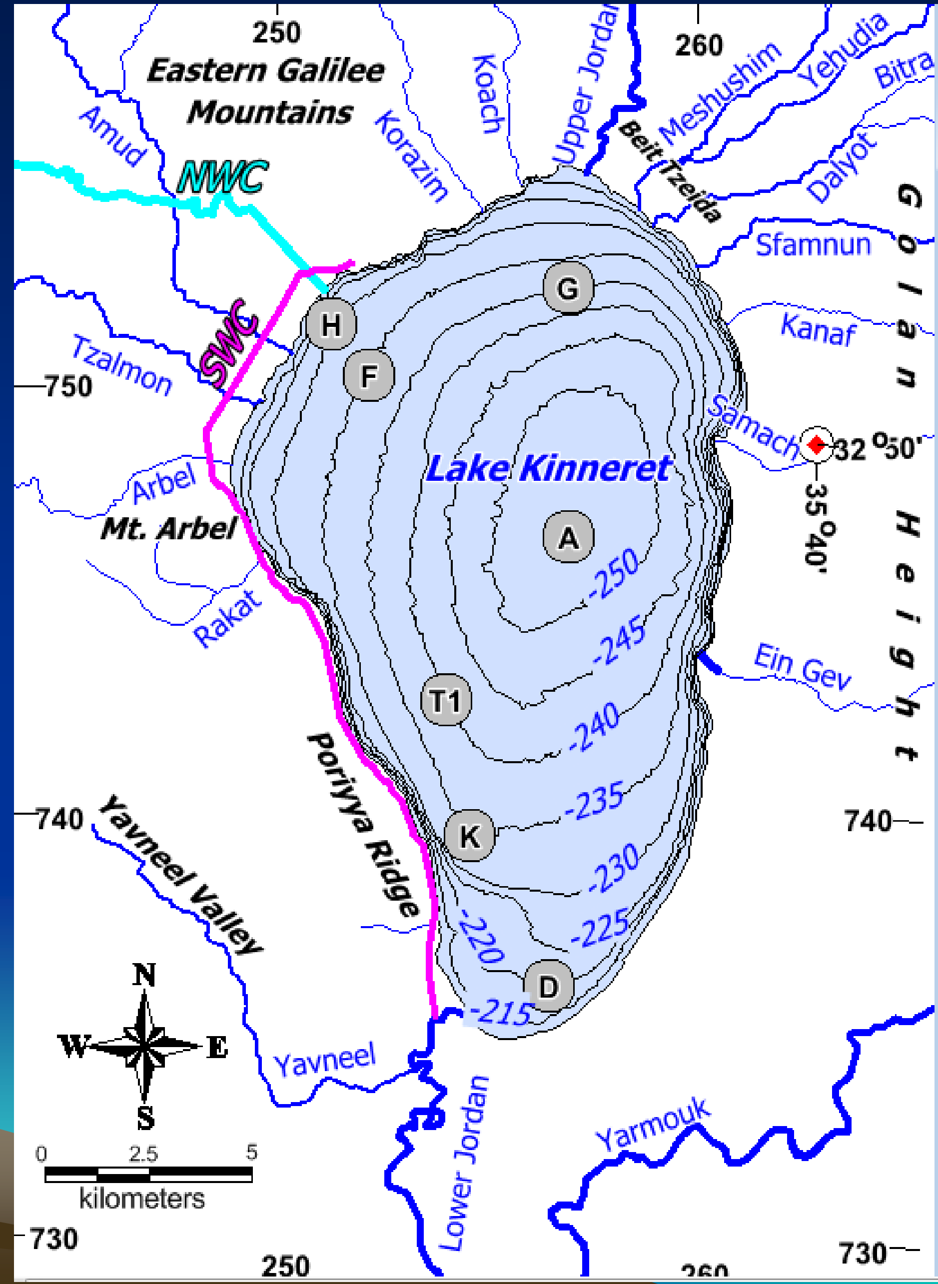
* sum: 1740

* runoff : 30

* Treated waste water 450

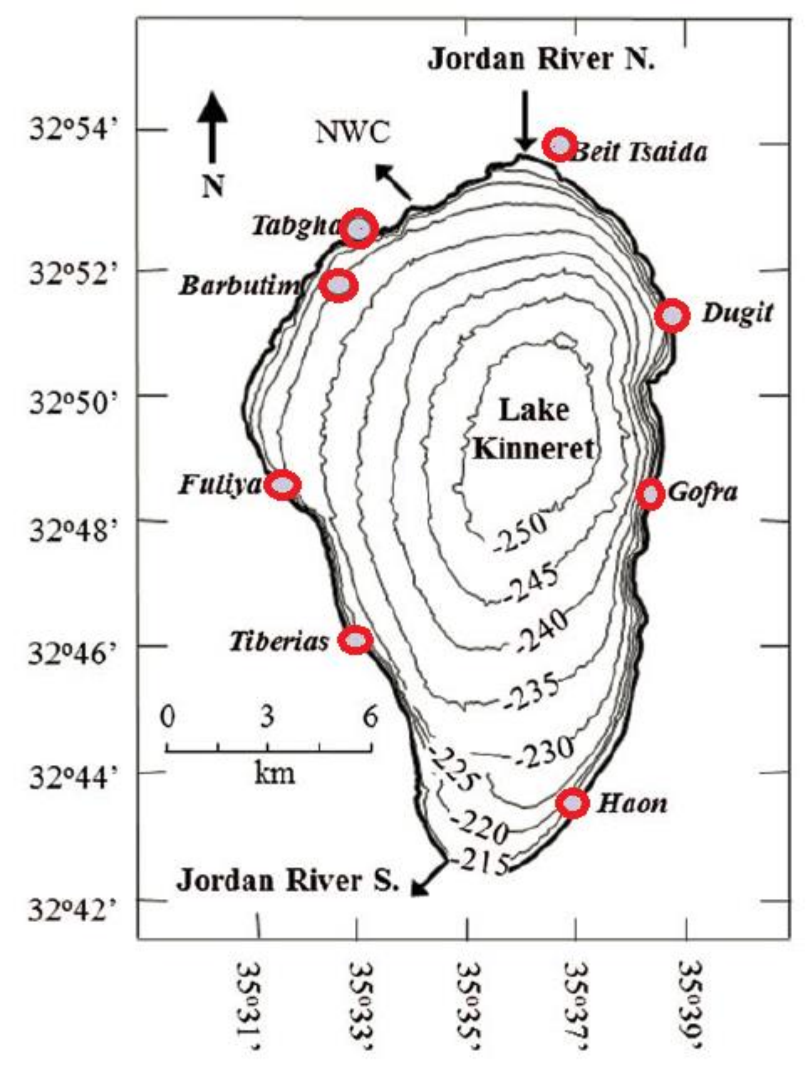
- in use 300
- Desalinization: 500

The National Water Carrier (NWC)



Inflow of saline springs into Lake Kinneret (Israel)

- The salinity of Lake Kinneret (190-300 ppm Cl^-), is significantly higher than the salinity of the water from the surface streams that flow to the lake (10-40 ppm Cl^-).
- The relatively high salinity of the lake is a result of the activity of saline springs located near the shoreline, and offshore springs at the bottom of the lake.
- The salinity of LK is considered as a major environmental problem in Israel, and reducing it is of high interest.

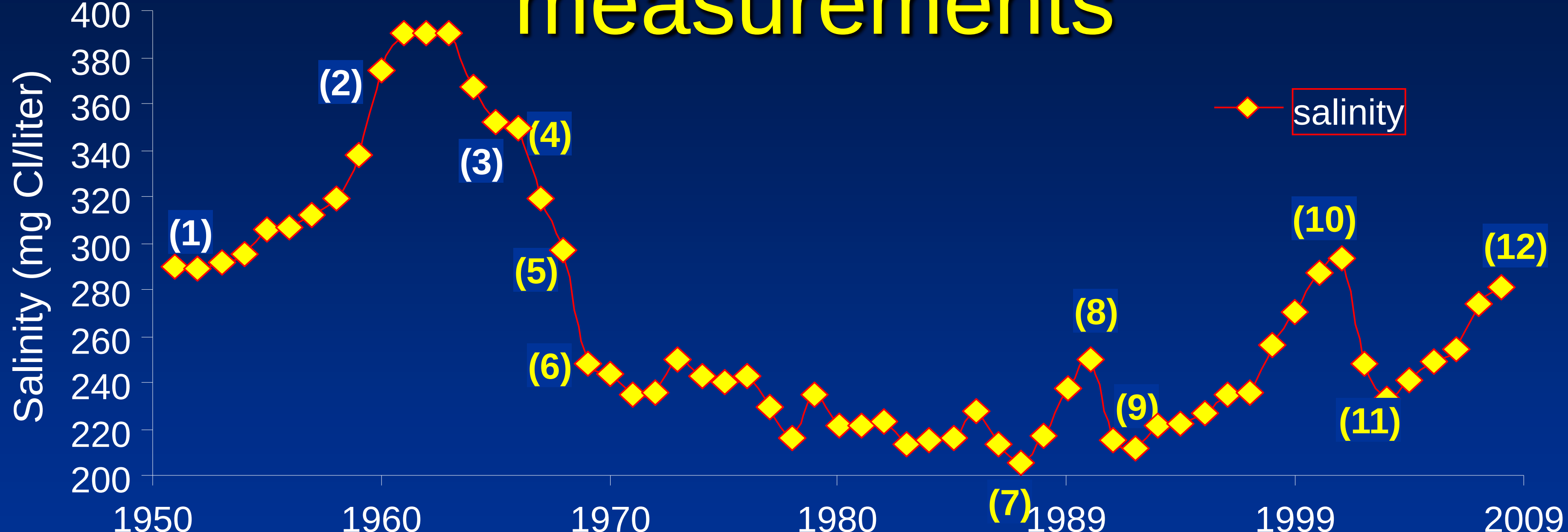


The annual average and standard deviations of water and chloride balances of Lake Kinneret 1987–2010

Characteristic	Units	Average	SD
Annual water inflows			
Direct rainfall	10^6 m^3	66.65	18.66
Streams	10^6 m^3	487.59	198.79
Groundwater	10^6 m^3	71.41	31.23
Artificial recharge	10^6 m^3	23.30	11.30
Total	10^6 m^3	648.95	202.41
Annual water outflows			
Evaporation	10^6 m^3	242.16	18.25
Pump and release	10^6 m^3	415.41	142.83
Total	10^6 m^3	657.58	143.99
Annual chloride inflows			
Direct rainfall and fallout	10^3 kg	333.25	93.29
Streams	10^3 kg	9,140.61	5,447.17
Groundwater	10^3 kg	91,712.39	16,976.82
Artificial recharge	10^3 kg	3,145.91	1,524.96
Total	10^3 kg	104,332.16	17,894.64
Annual chloride outflows			
Pump and Release	10^3 kg	98,623.57	33,018.22
Lake			
Cl^- concentration	mg L^{-1}	241.76	24.97
Average chloride mass	10^3 kg	920,693.57	48,728.32
Average residence time	Year	10.50	3.95

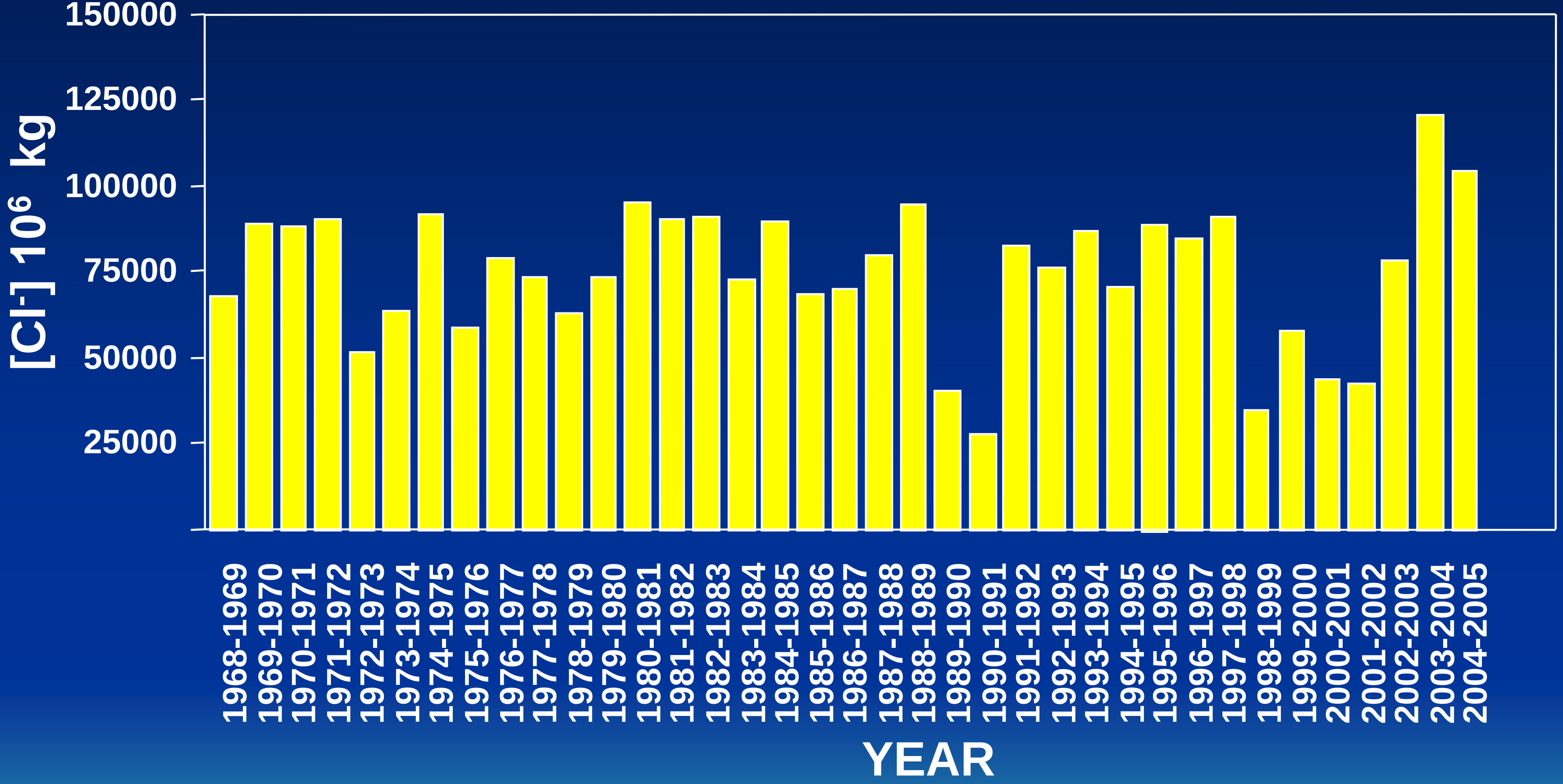
SD standard deviation

The history of Lake Kinneret salinity measurements



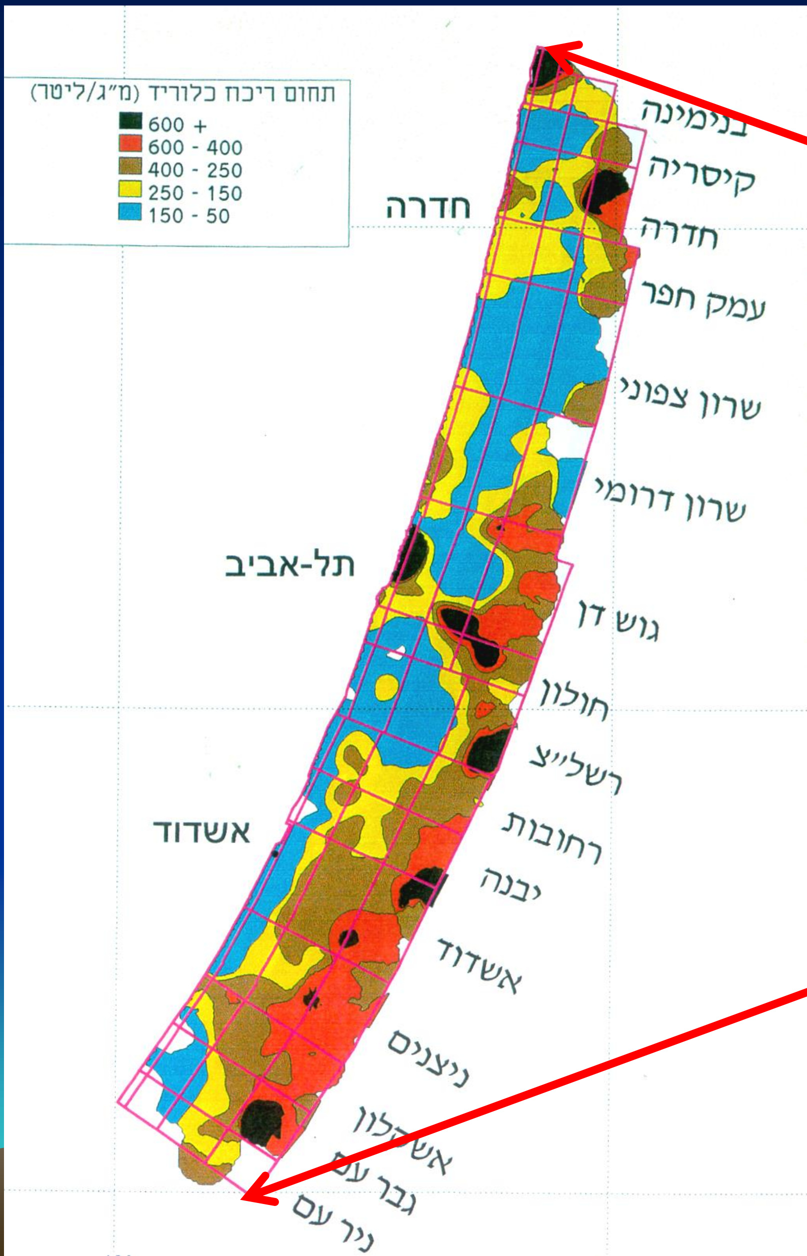
1. **During the years 1954-1962 significant increase.**
2. **Between 1961-1963 reaching peak values of ~390 ppm Cl^-;**
3. **In 1964, the NWC became operative, chloride content began to drop;**
4. **SWC was fully operated in January 1965, preventing an average of ~55,000 ton Cl^- from flowing to the lake, salinity drop enhanced.**
5. **Lake salinity further enhanced by the exceptionally rainy winter of 1968-69 (inflows of 200% compared to an average year).**
6. **The lowest lake salinity, 192 ppm Cl^-, reported in May 1988.**
7. **Increased to 250 ppm Cl^- following three dry winters.**
8. **Decreased to ~210 ppm Cl^- following the exceptionally rainy winter of 1991-1992.**
9. **Increased to ~290 ppm Cl^- from the end of the winter 1993-1994 to the winter of 2001-2002.**
10. **Following the extreme winter of 2002-2003 the salinity reduced to ~230 ppm Cl^-.**
11. **From 2004 to 2011 the salinity bounced again to ~280 ppm Cl^-.**

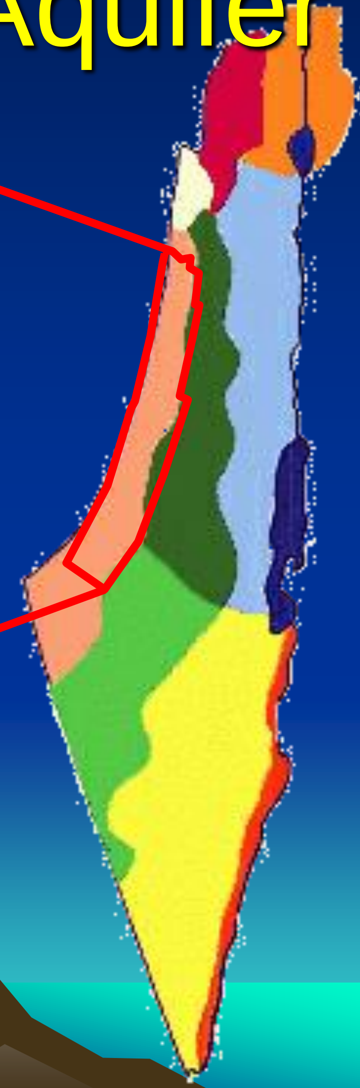
[Cl^-] mass exported from Lake Kinneret

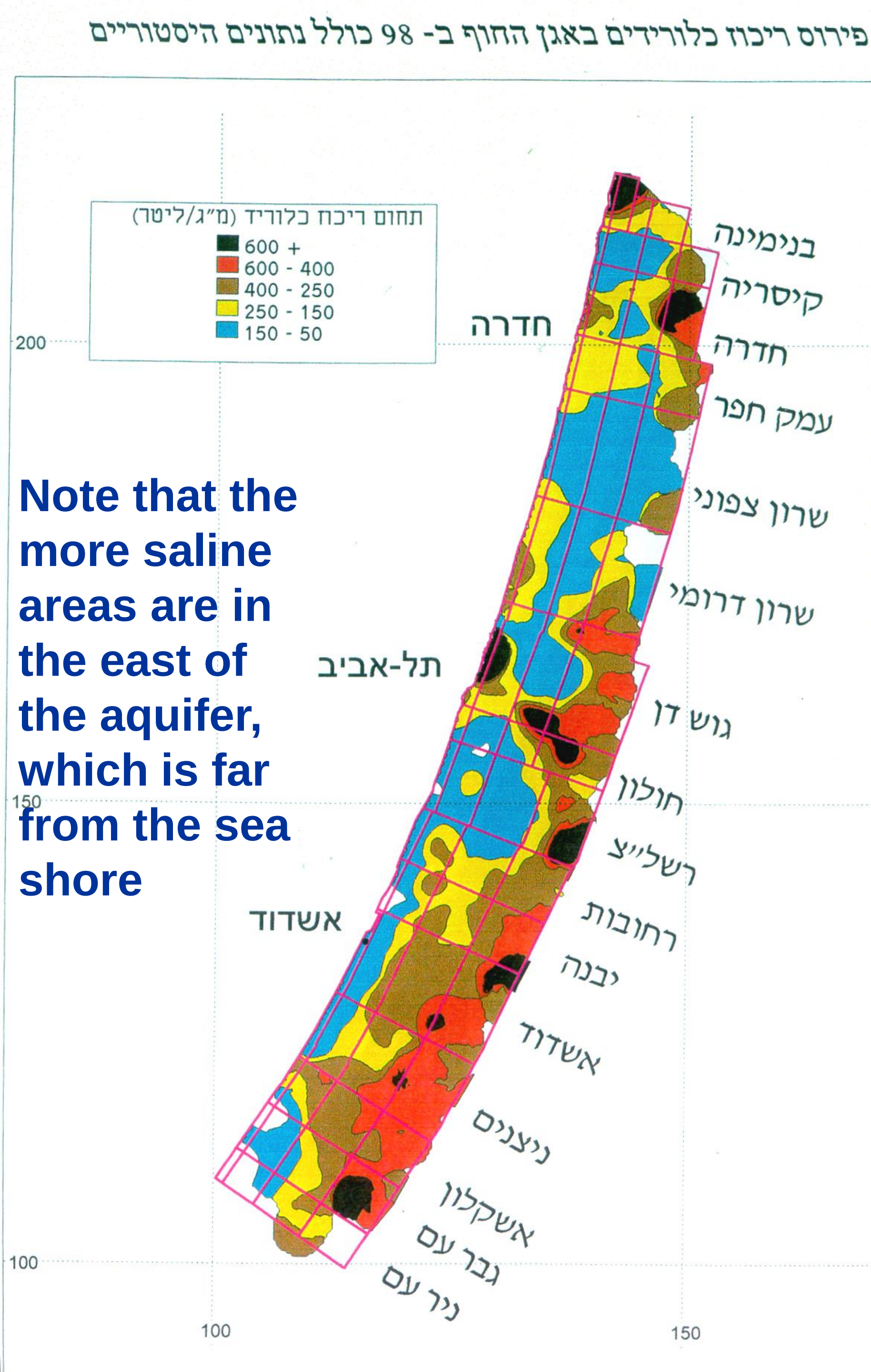


- Annual chloride export is 330 million m^3. Assuming average concentration of 230 mgCl/L it sums up to 75,900 $\times 10^6$ kg

What happened to the salinity of the Coastal Aquifer







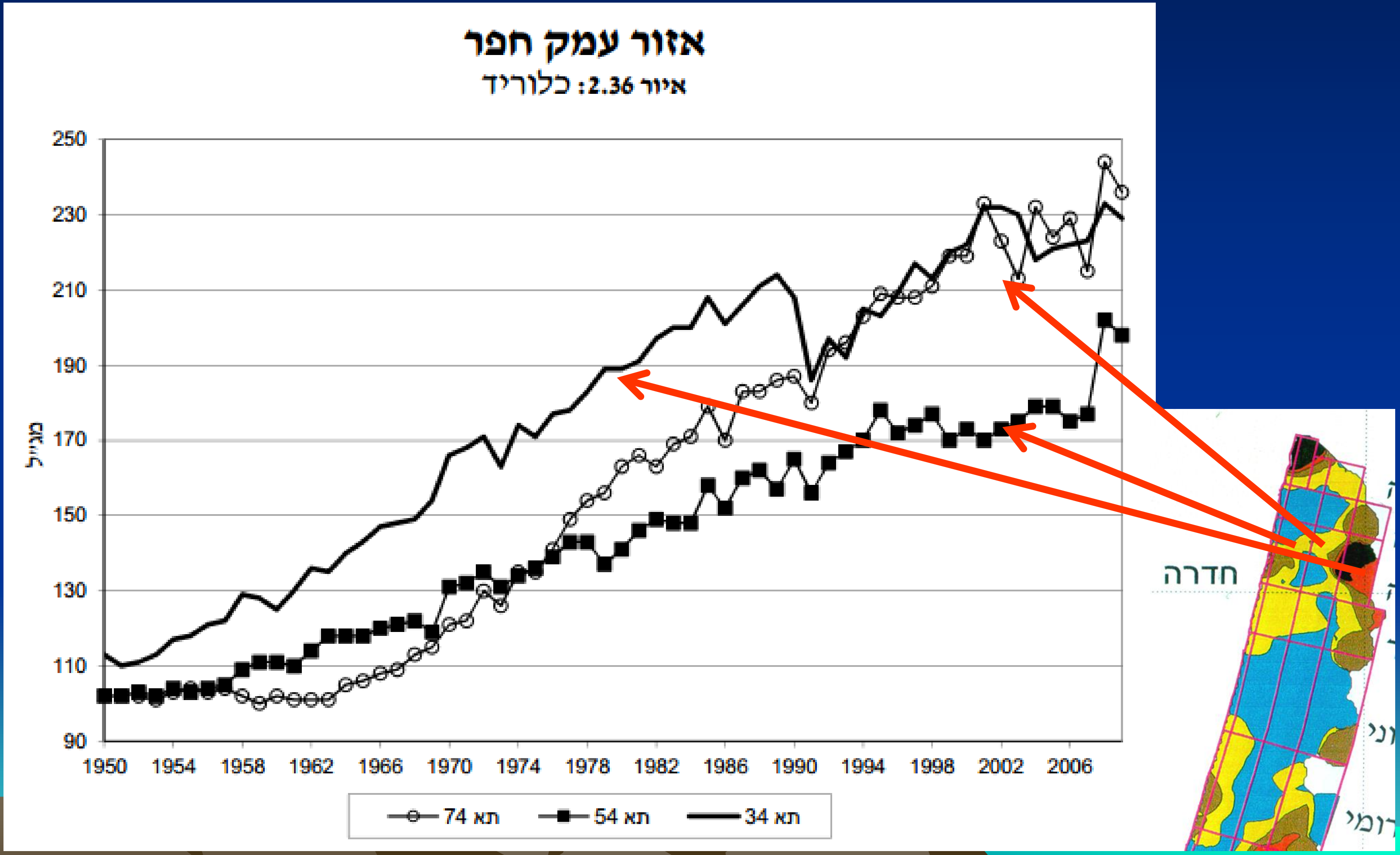
Note that the more saline areas are in the east of the aquifer, which is far from the sea shore

[Cl$^-$] concentration in the Coastal Aquifer

- The Cl concentration in the coastal aquifer is 50 – 600 mg/l. This salinity increase annually with 1 mg/l.
- The irrigation with the relatively high Lake Kinneret water, and the strong evaporation processes in the region adds significantly to the salinization of the aquifer
- Domestic use usually adds 100 mg/l of Cl to the waste water.
- Irrigation with treated waste water, and the techniques of storing them in ground water (SHAFDAN project) adds salinity to groundwater
- Regular waste water treatment plants do not remove salinity from the water, and therefore waste water are usually more saline than original Lake Kinneret water.

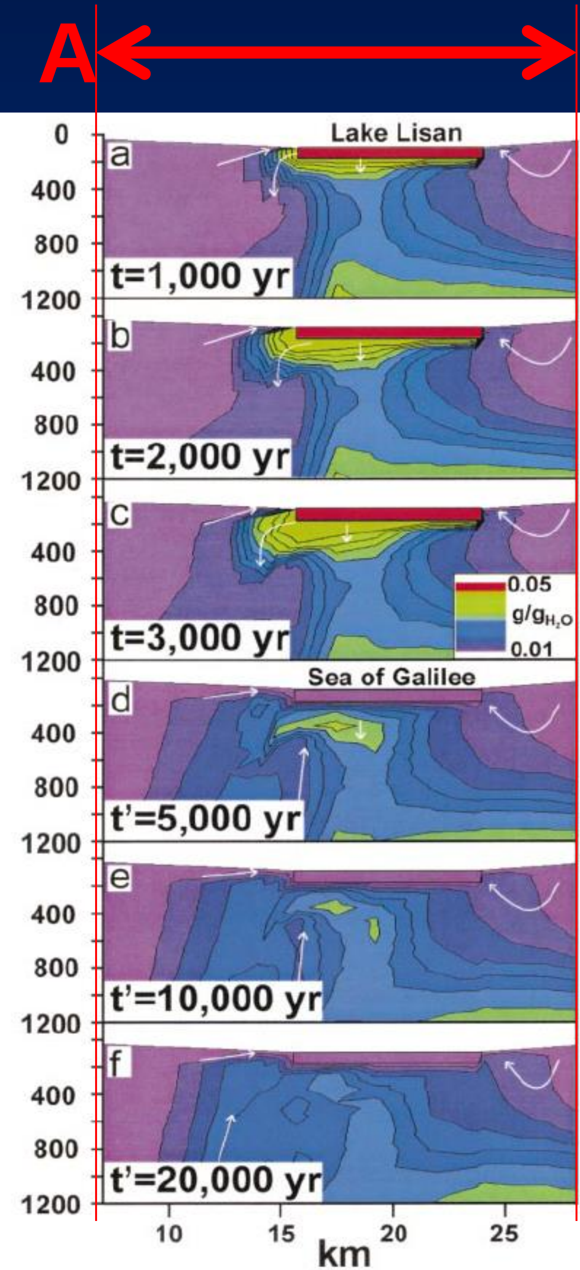
[Cl⁻] concentration changes in the Coastal Aquifer 1950-2008

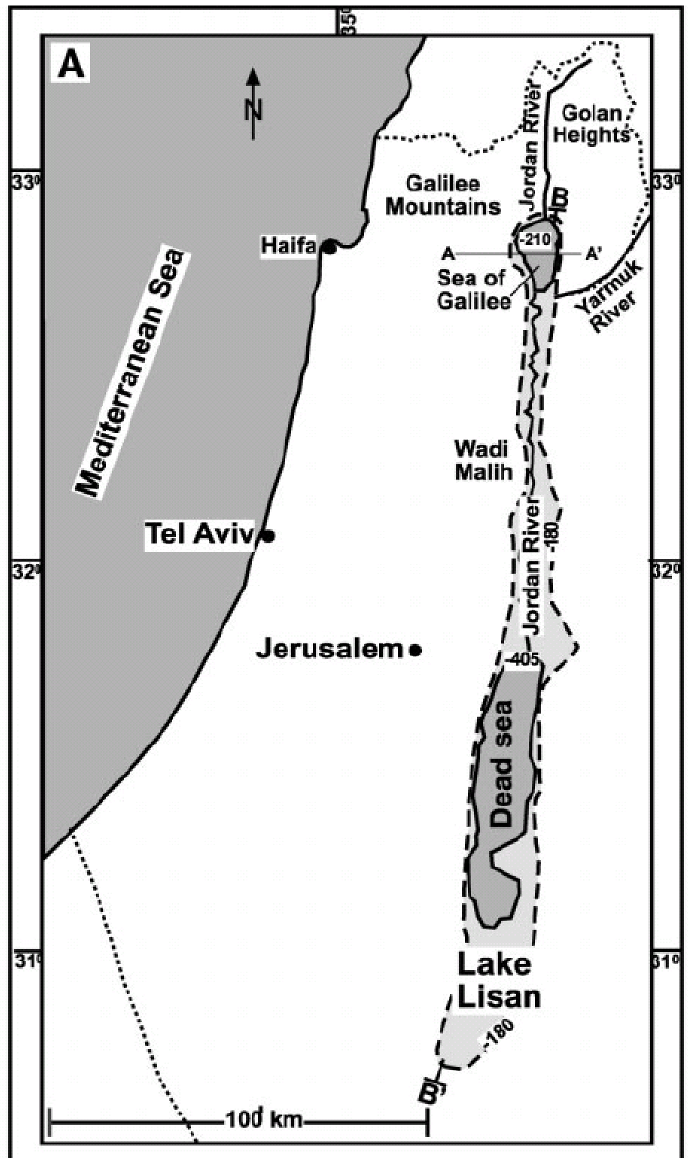
Cl concentration mg/L



Year

What is the source of the solutes

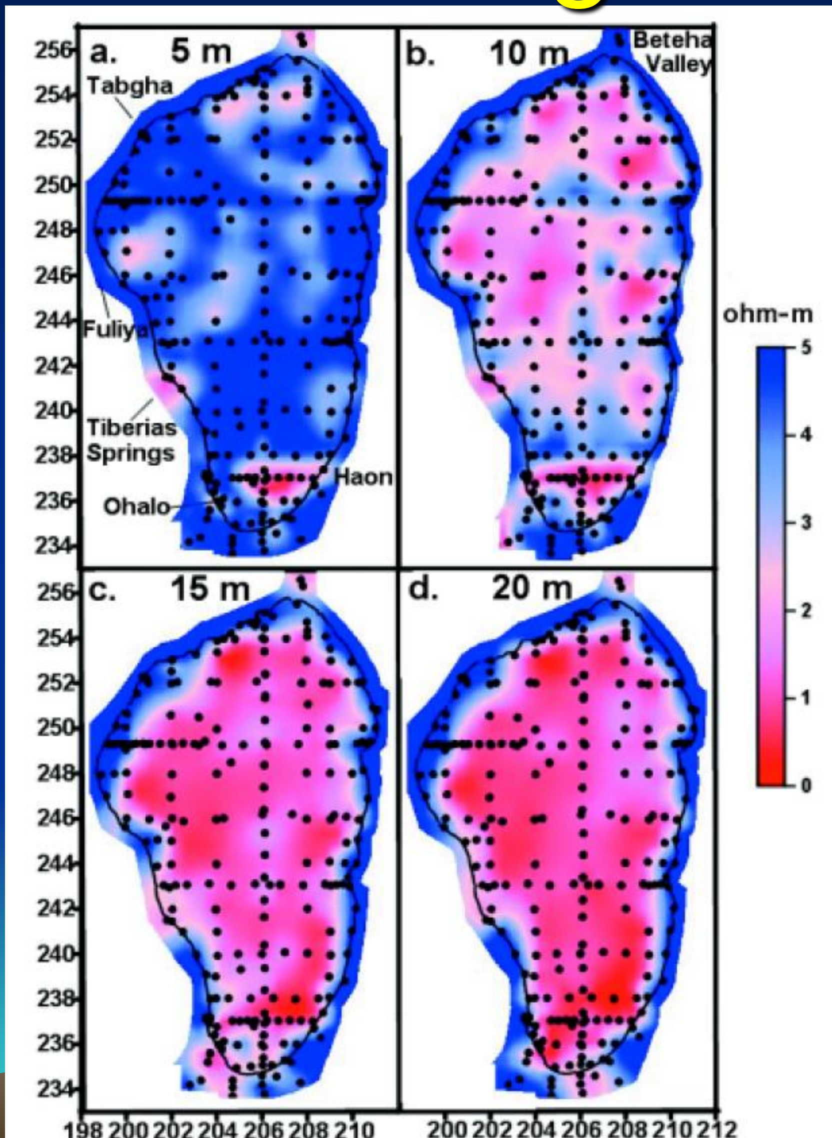




Right: Map of lakes from the past (20,000 years ago) and present along the Dead Sea Rift. Maximum coverage of Lake Lisan, with salinity of 100 to 300 g\liter. Maximum lake level was about 180 meters below sea level, for few thousand years.

Left: Salinity and flow directions during the stage that Lisan level was 180 meters below sea level. The development of salinity profile within 1200 meters deep bedrock, for 3,000 years as a result of the penetration of high salinity water from the surface. Bottom: 17,000 years since withdrawn Lake Lisan.

Lake Kinneret is a fresh water lake "floating" on a solute ground

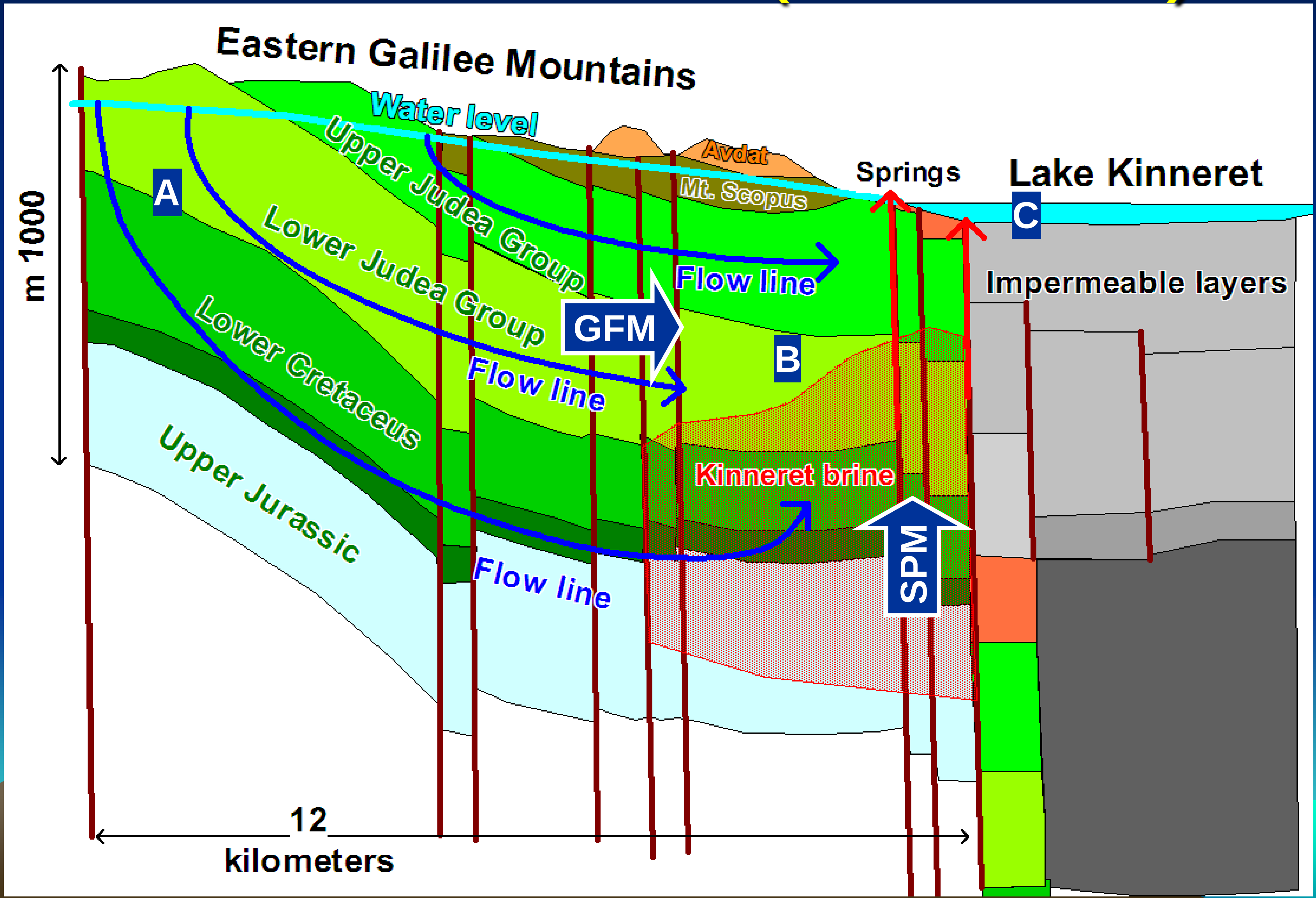


Salinity measured using TDEM at different depths (5, 10 15 and 20 meters) below the bottom of the Sea of Galilee in 1999. Red indicates the high salinity of ~10,000 mg/liter, and blue indicates the relative washed areas where salinity is less than 500 mg/liter. Black dots indicate the points at which the survey was conducted.

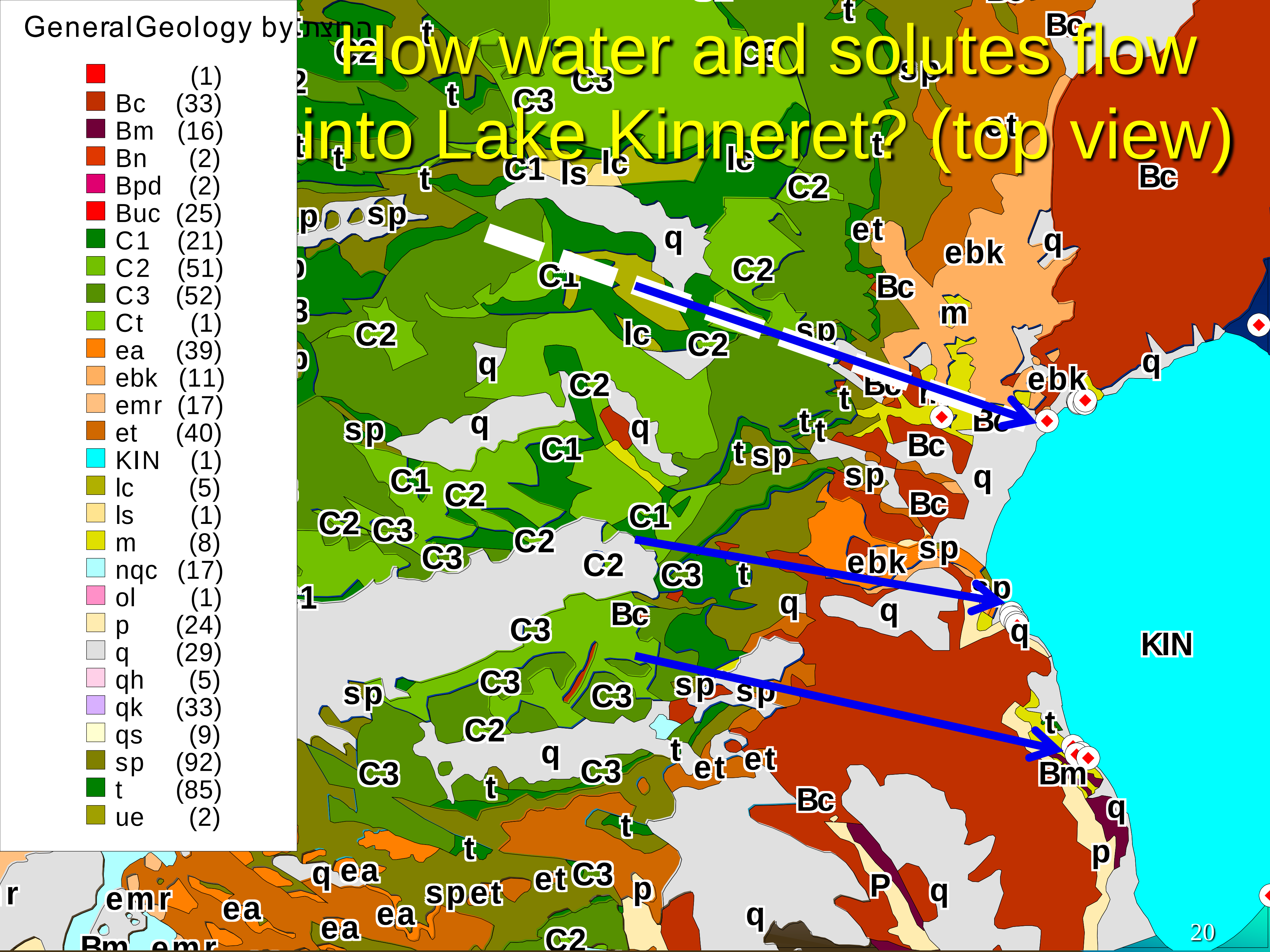
Hurwitz, S., Stanislavsky, E., Lyakhovsky, V., & Gvirtzman, H. (2000). Transient groundwater-lake interactions in a continental rift: Sea of Galilee, Israel. Geological Society of America Bulletin, 112(11), 1694-1702.

Hurwitz, S., Goldman, M., Ezersky, M., & Gvirtzman, H. (1999). Geophysical (time domain electromagnetic model) delineation of a shallow brine beneath a freshwater lake, the Sea of Galilee, Israel. Water Resources Research, 35(12), 3631-3638.

How water and solutes flow into Lake Kinneret? (side view)



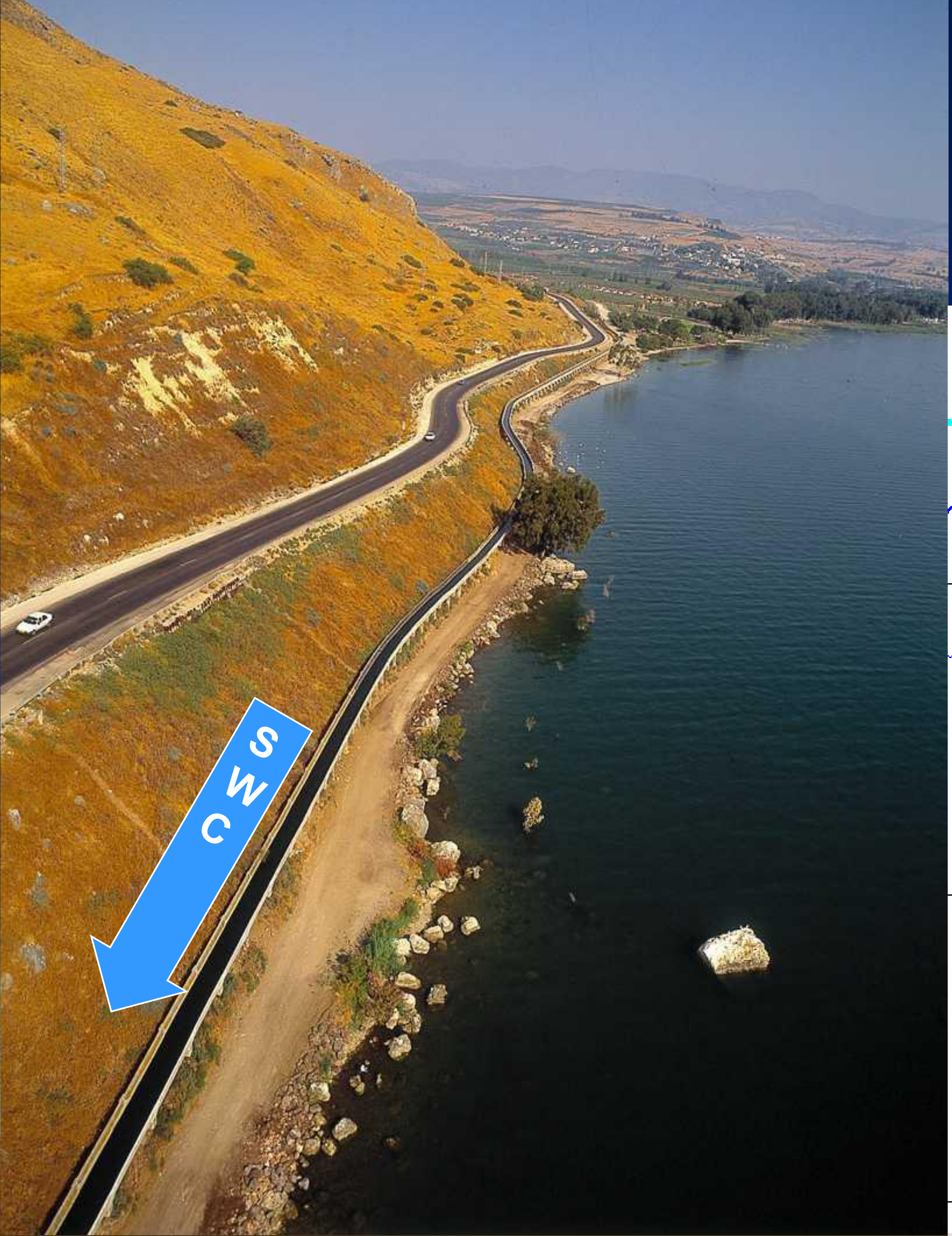
How water and solutes flow into Lake Kinneret? (top view)

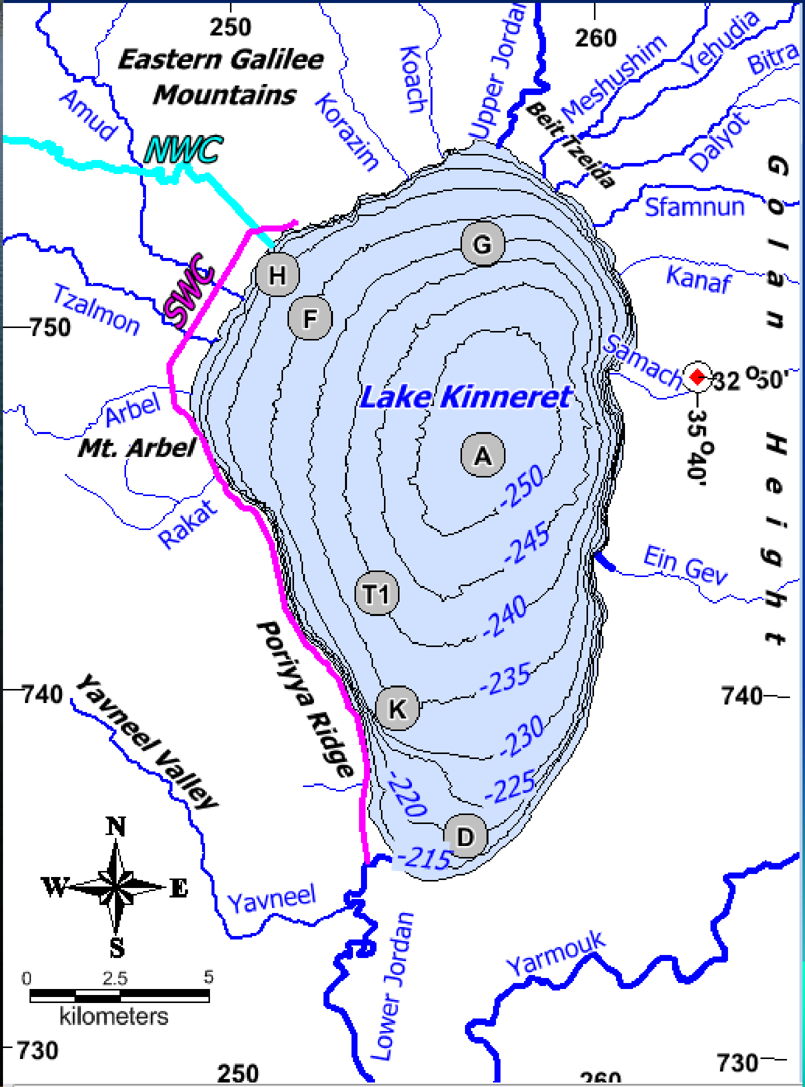


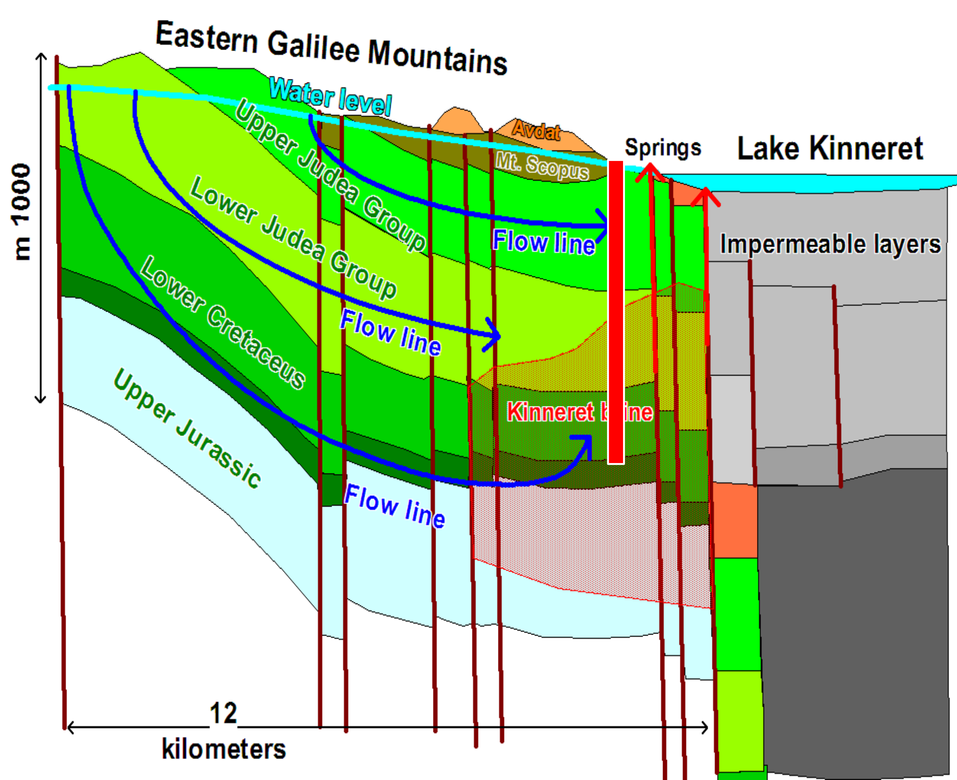
Practices to reduce Lake Kinneret salinity

1. Capture the most saline springs in the west side of the lake and divert it around the lake to the Lower Jordan River (the saline water carrier SWC)
2. Pump the saline water near the lake directly from the aquifer, and direct it to the SWC.
3. Study the mechanism of salinization and decide on water management rules that will minimize lake salinization.

1. The saline water carrier (SWC)



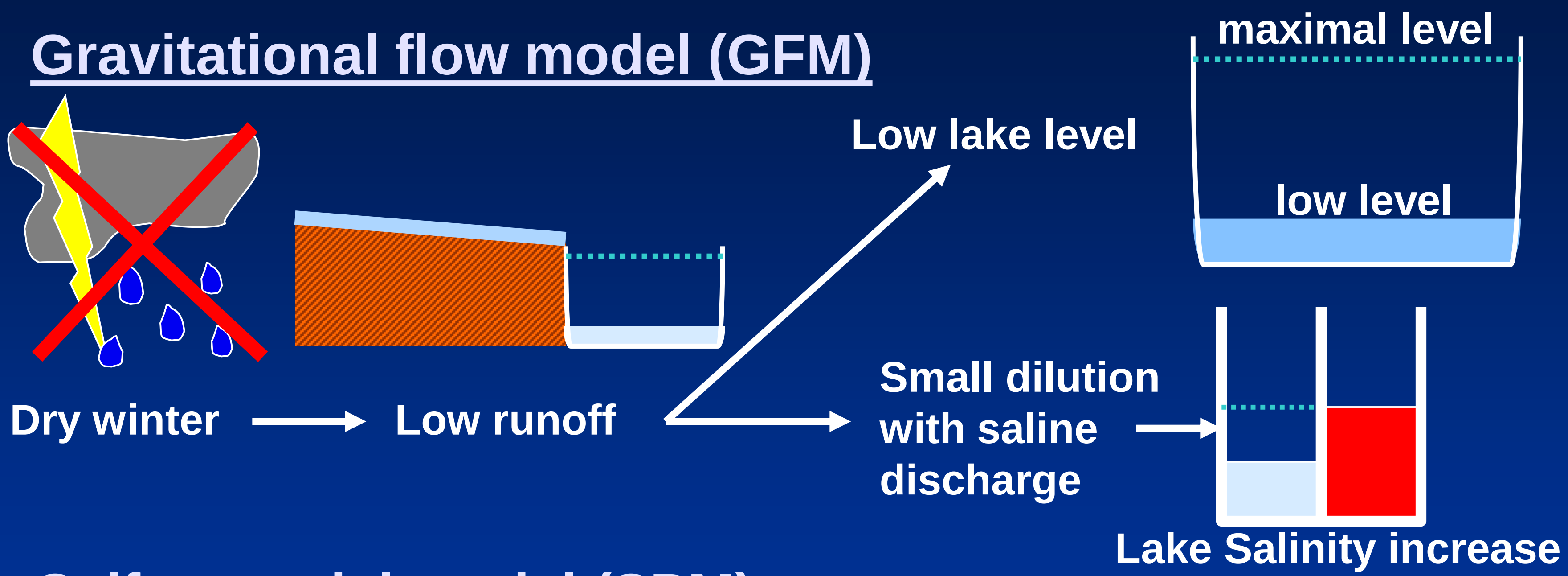




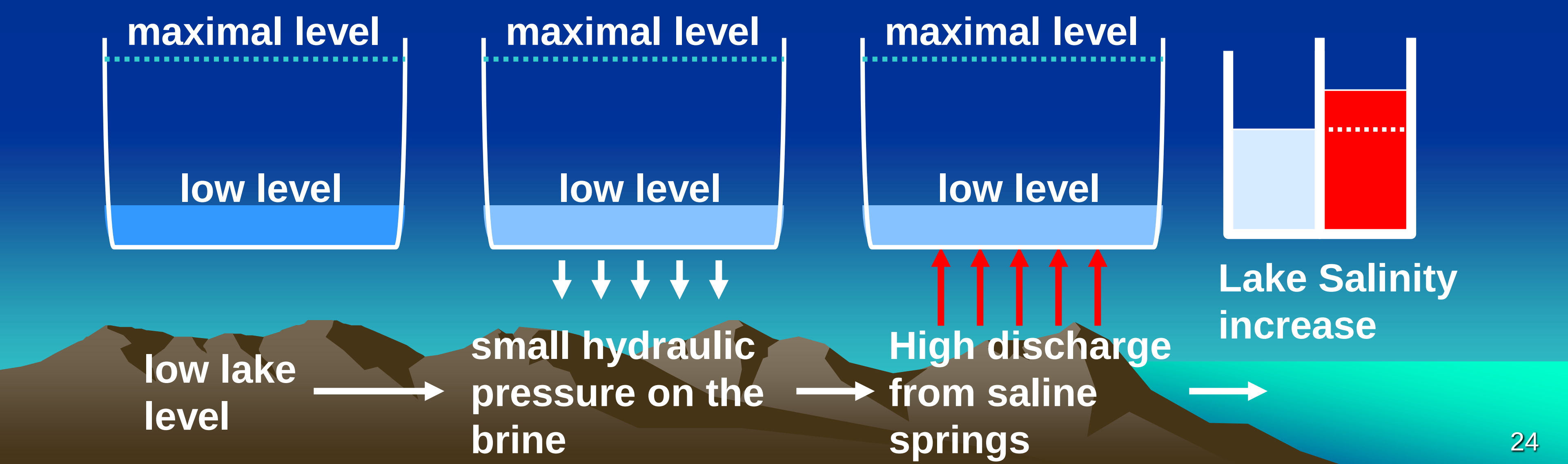
2. Pump the saline water directly to the SWC

3. Study the mechanism of salinization

Gravitational flow model (GFM)

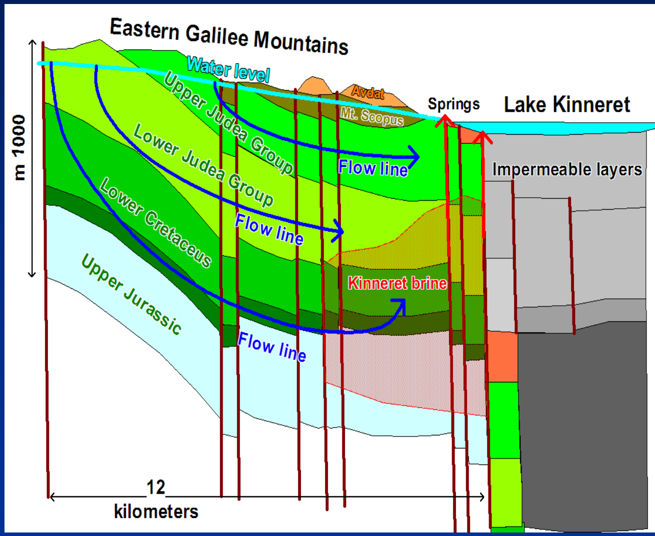


Self potential model (SPM)



Self potential model (SPM)- Major arguments

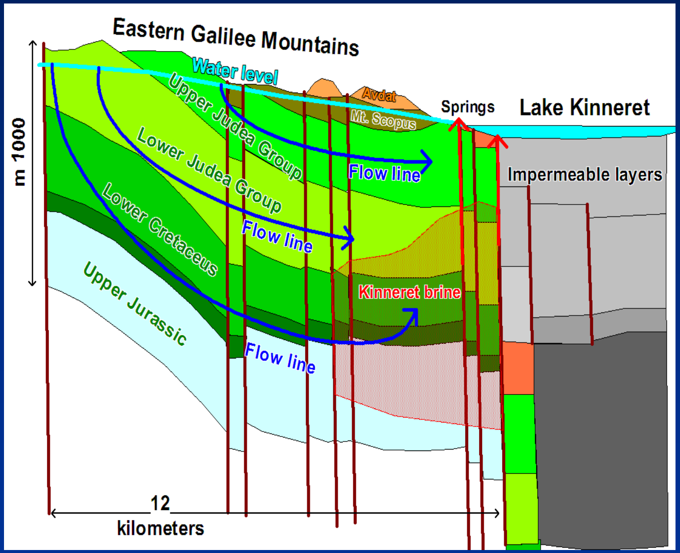
1. Fresh groundwater levels in the Eastern Galilee (west of the lake) make a counterbalance to the driving pressure and therefore should not be decreased. Consequently, pumping of groundwater from this area should be limited.



2. The lake level should not be reduced below a prescribed level. Lowering the water levels in both the lake and adjacent aquifers will increase the hydraulic gradient between the saline water and lake, and thus intensive seepage of saline water through the lake sediments will take place.

Gravitational flow model (GFM) Major arguments

1. The flow of saline springs depends on a ~ 100-m head difference between aquifers in the Eastern Galilee and Lake Kinneret, and therefore the 1–4 m change in the lake water level has negligible effect on this flow.
2. Reduced hydraulic heads in deep aquifers in the Galilee will lead to reduction of the pressure applied on the deep saline reservoir, and therefore salt flux into the lake will decrease.



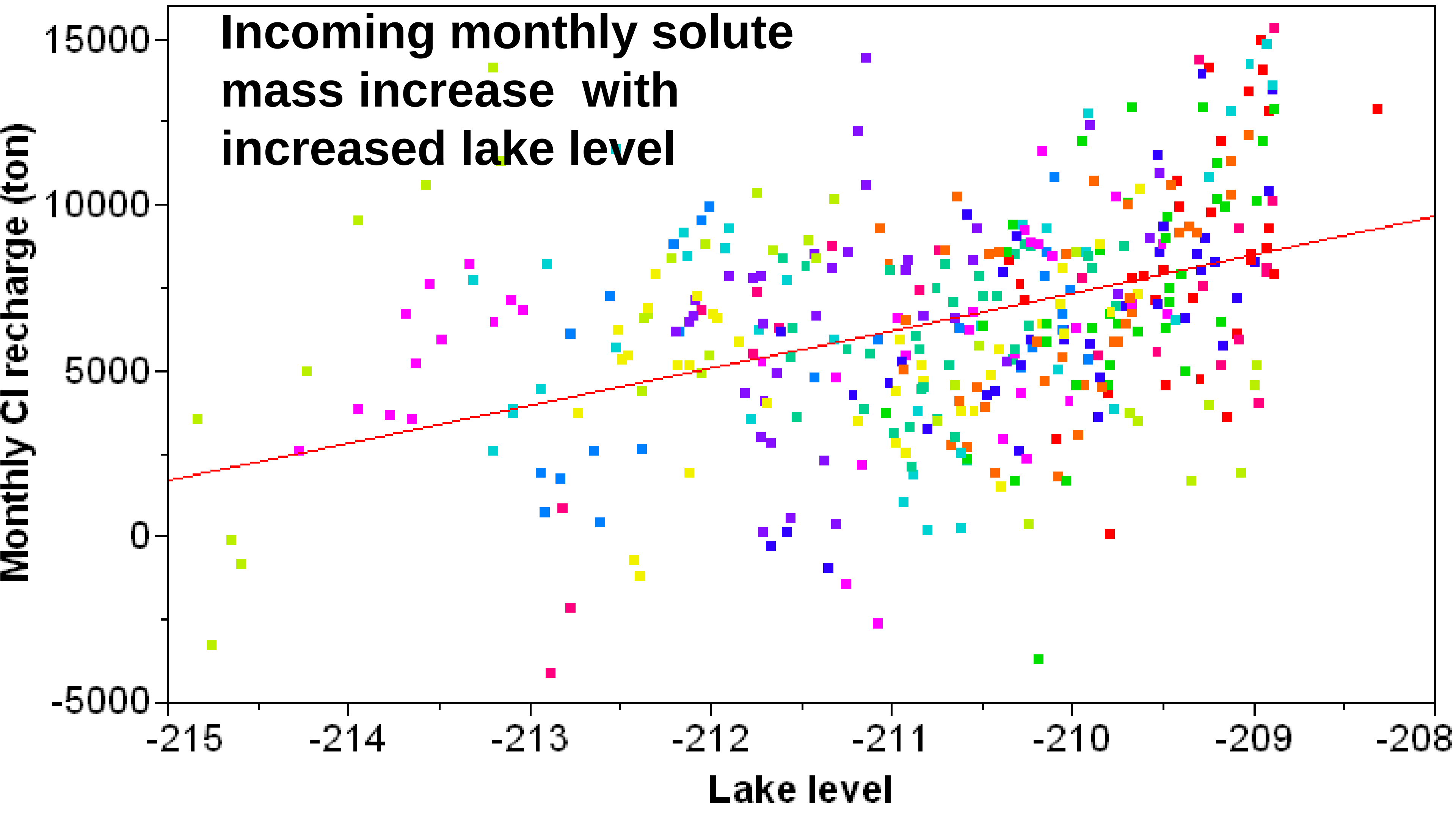
The implications of the SPM-GFM arguments on operational decisions

1. The SPM theory was dominating.
2. Pumping of groundwater from the Eastern Galilee area was limited by the Israeli Water Authority for four decades (1960–2000).
3. The lake level should not be reduced below a prescribed "red line," which was posed for many years on − 212 m, and later on − 213 m a.m.s.l.

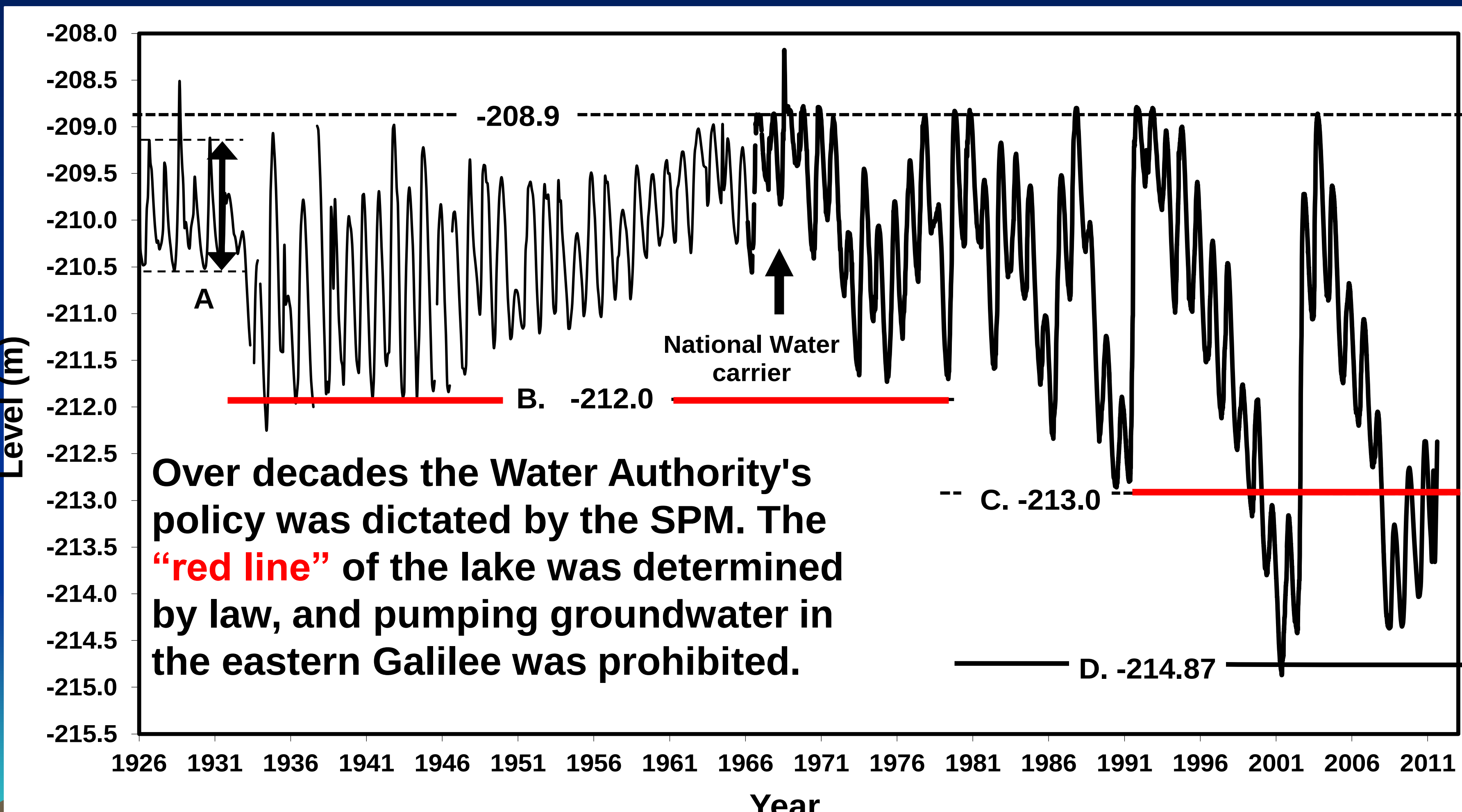
New studies in 1995–2000

A series of studies during the years 1995–2000 came up with an important understanding that the GFM mechanism controls the discharge of the saline springs. These findings resulted in the decision to lower the "red line" during 1999–2001 without the fear of enhanced salinization.

Incoming monthly solute mass vs lake level for the years 1969-2000

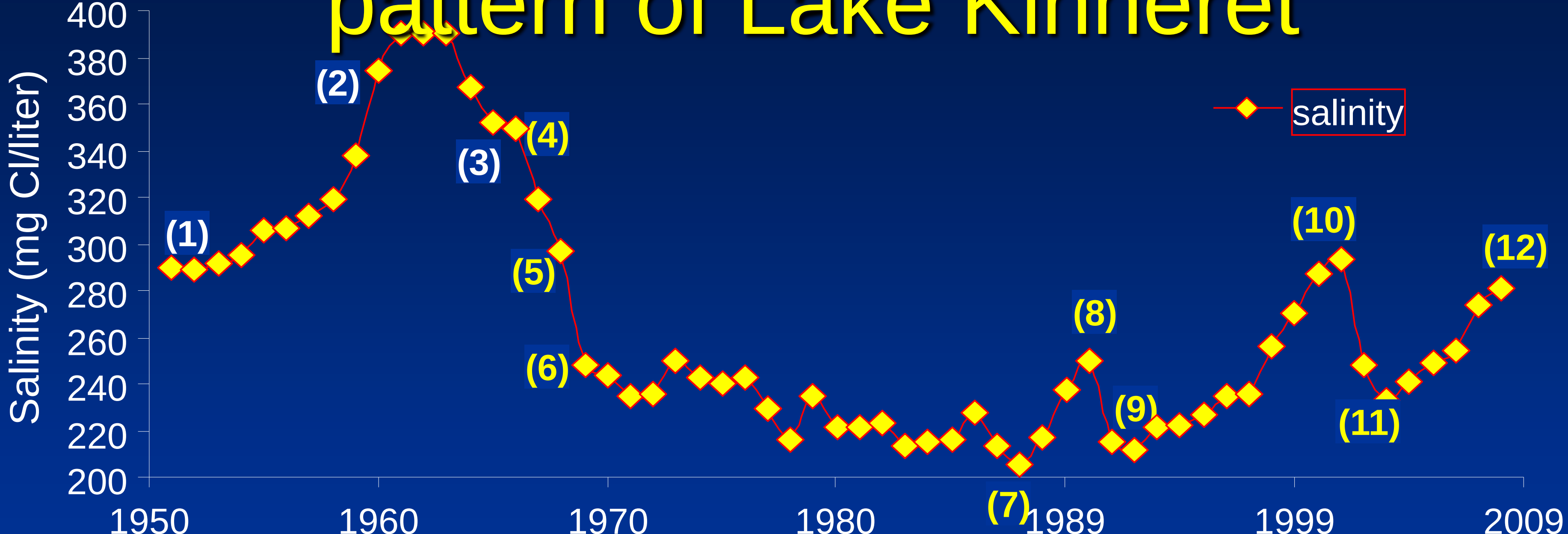


Lake Kinneret level and the **Red Line**



Over decades the Water Authority's policy was dictated by the SPM. The "red line" of the lake was determined by law, and pumping groundwater in the eastern Galilee was prohibited.

Understanding the historic salinity pattern of Lake Kinneret



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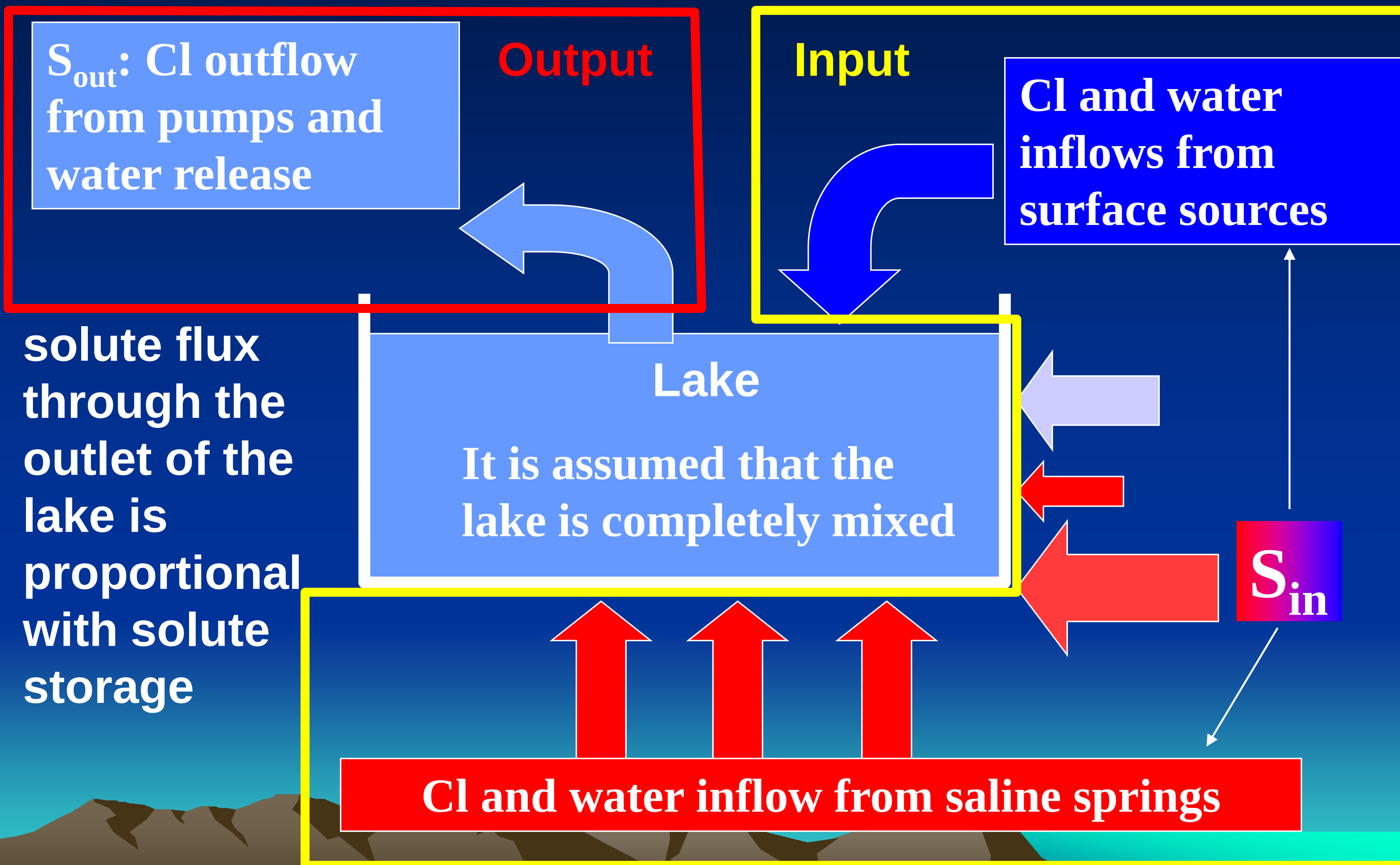
Lake Salinity Model (LSM)

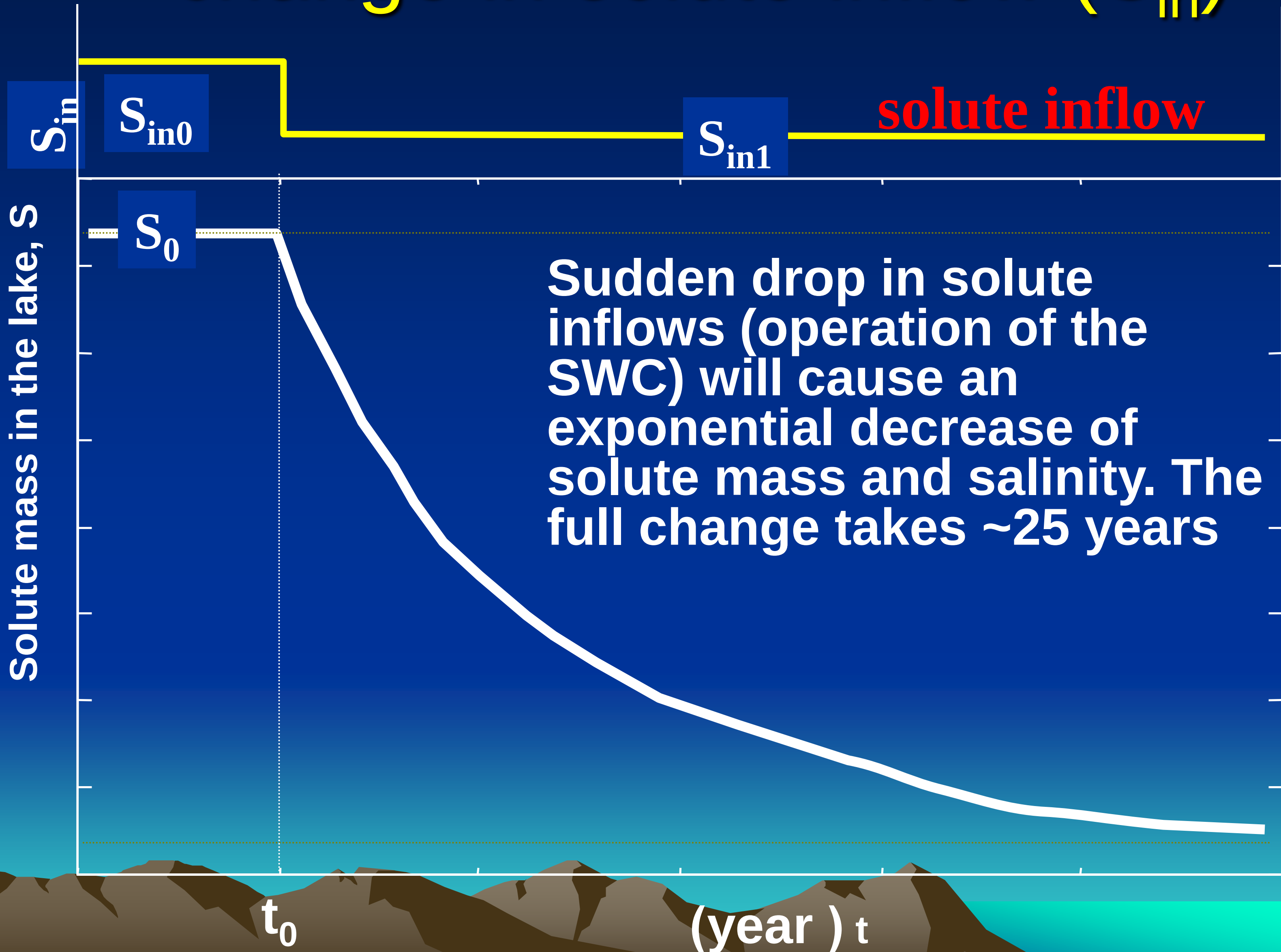
1. Rimmer, A. (2003). The Mechanism of Lake Kinneret Salinization as a Linear Reservoir. *Journal of Hydrology*, *281/3 pp. 177-190*.
2. Rimmer A., M. Boger, Y. Aota and M. Kumagai, 2006. A Lake as a Natural Integrator of Linear Processes: Application to Lake Kinneret (Israel) and Lake Biwa (Japan). *Journal of Hydrology, 319/1-4, pp. 163-175.*

The Lake Salinity Model (LSM)

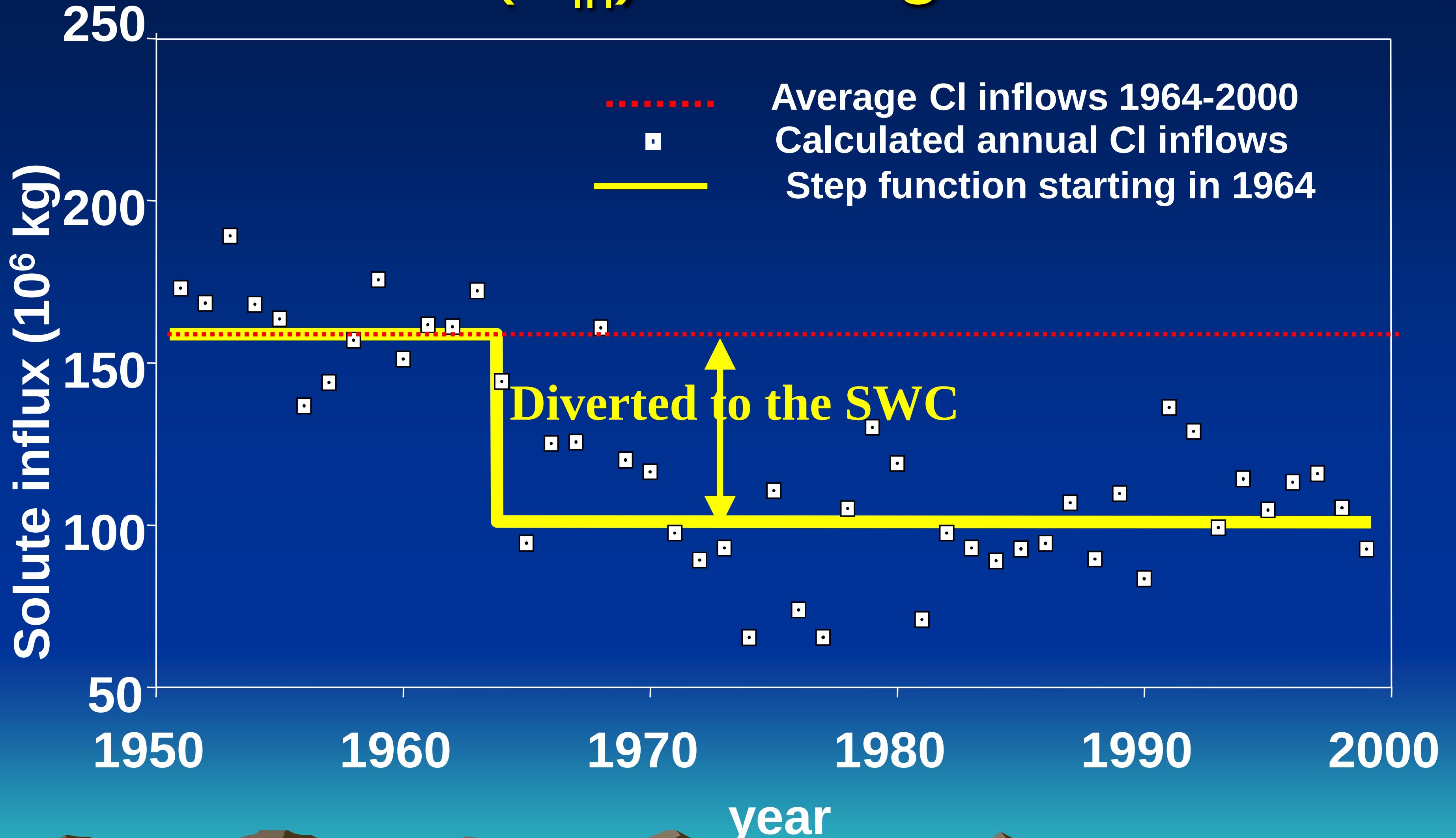
solute flux through the outlet of the lake is proportional with solute storage



Schematic lake salinity response to change in solute inflow (S_{in})

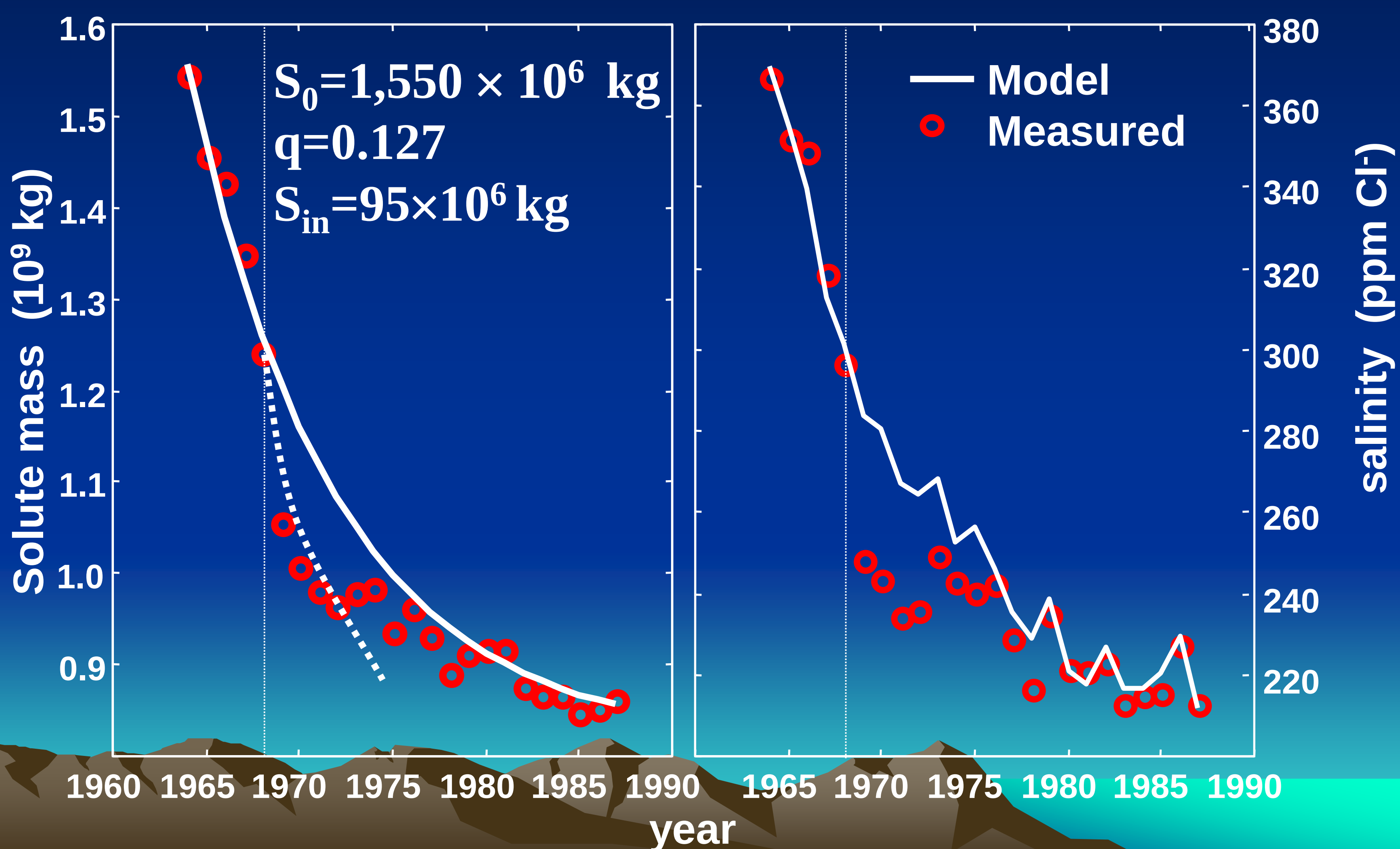


The actual step change in solute inflow (S_{in}) starting in 1964

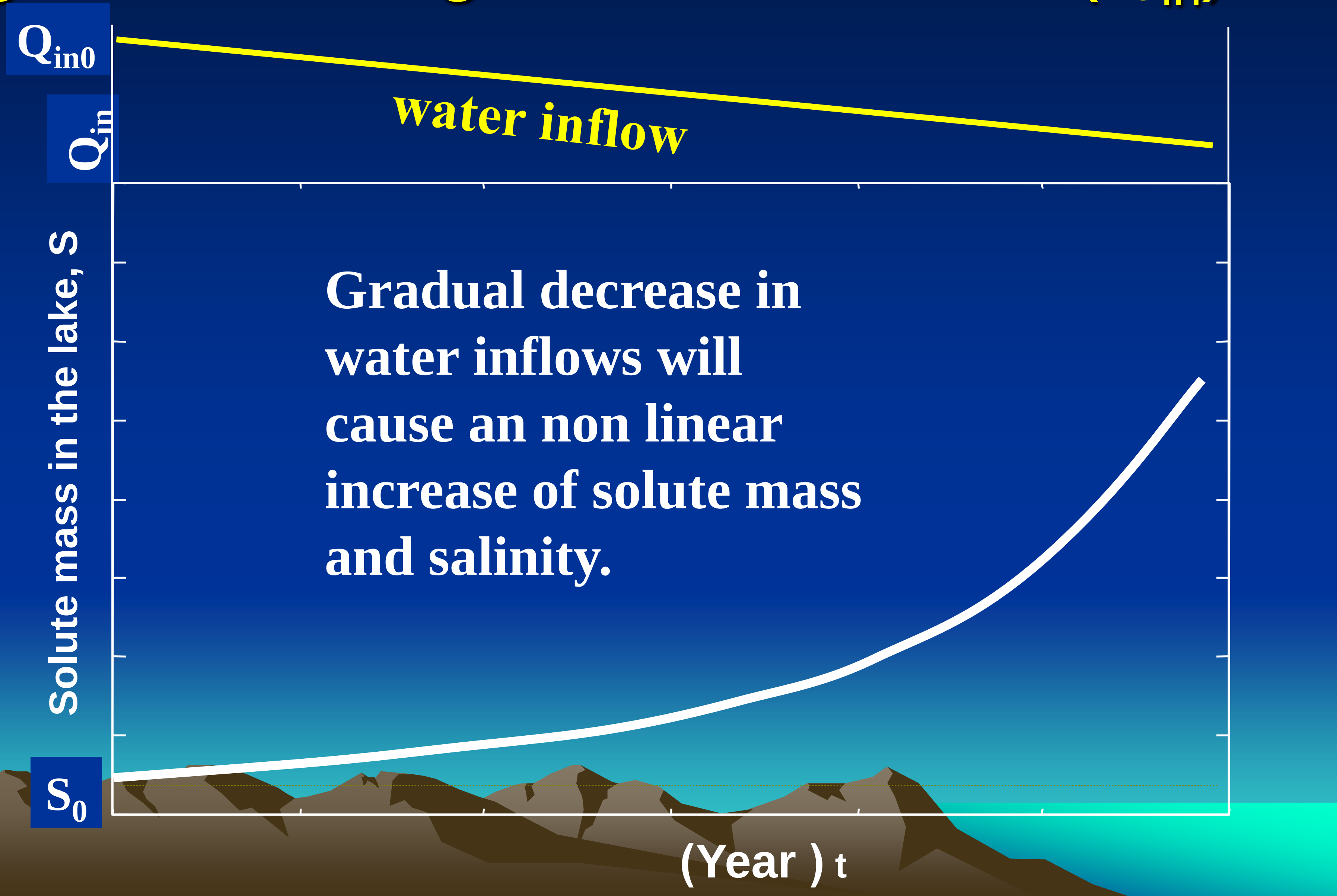


Model result for 1964-87

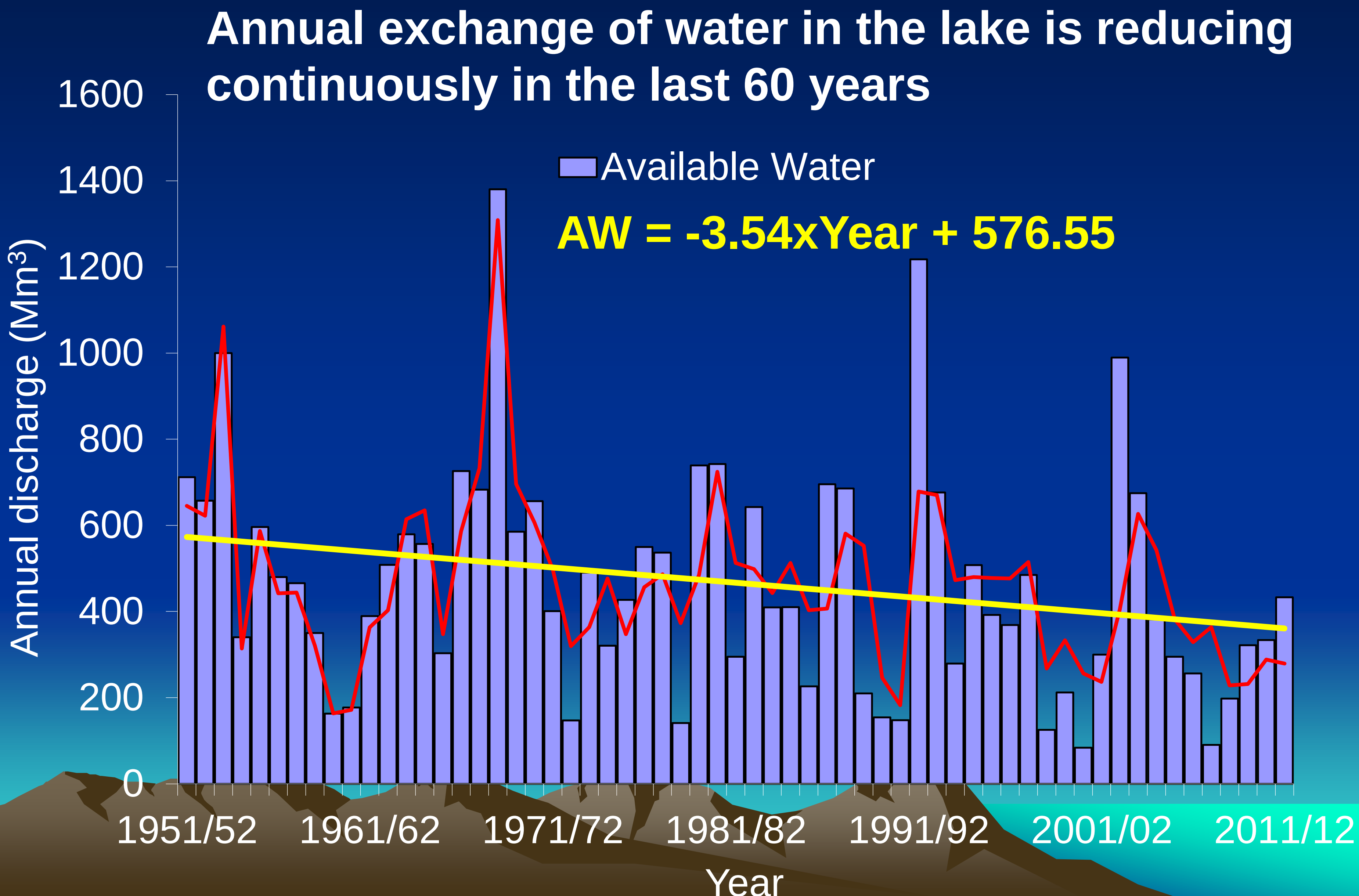
The reduction in solute mass and salinity between 1964 and 1987 is an obvious result of the operation of the SWC in 1964



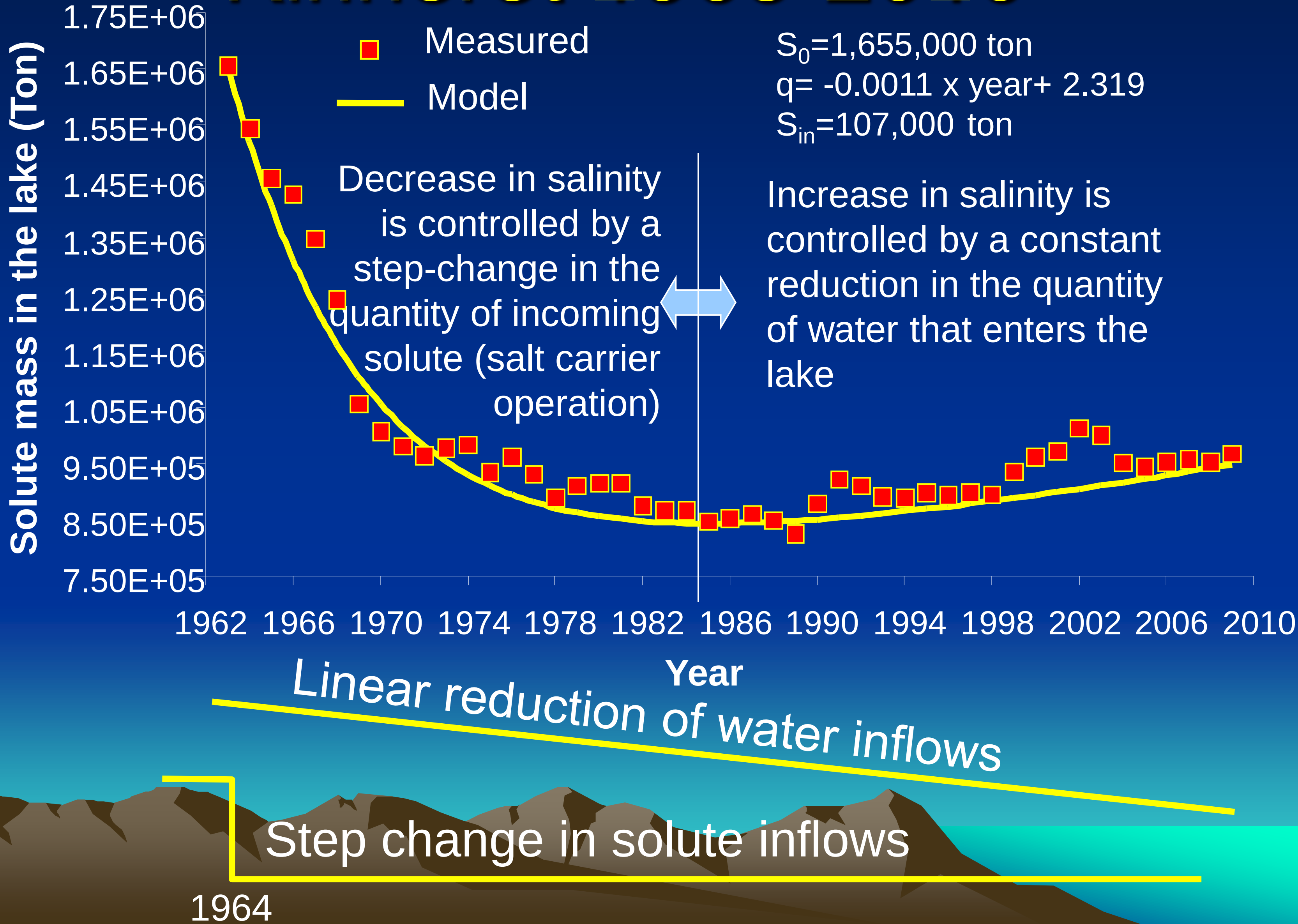
Schematic lake salinity response to gradual change in water inflow (Q_{in})



The actual gradual change in water inflow (Q_{in}) since 1951

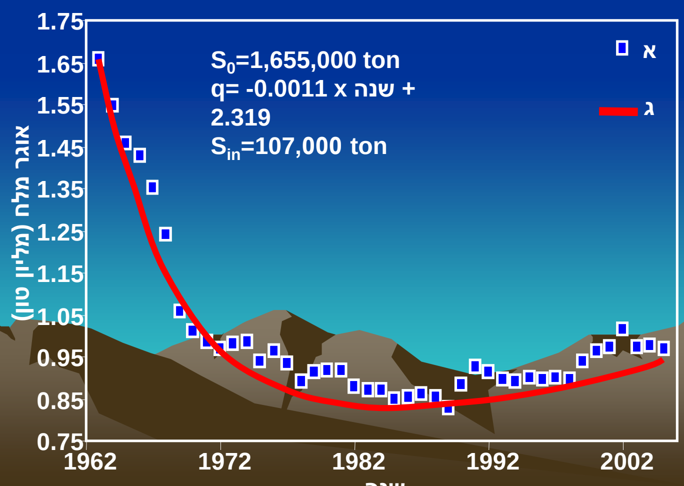


Changes in solute mass in Lake Kinneret 1963-2010



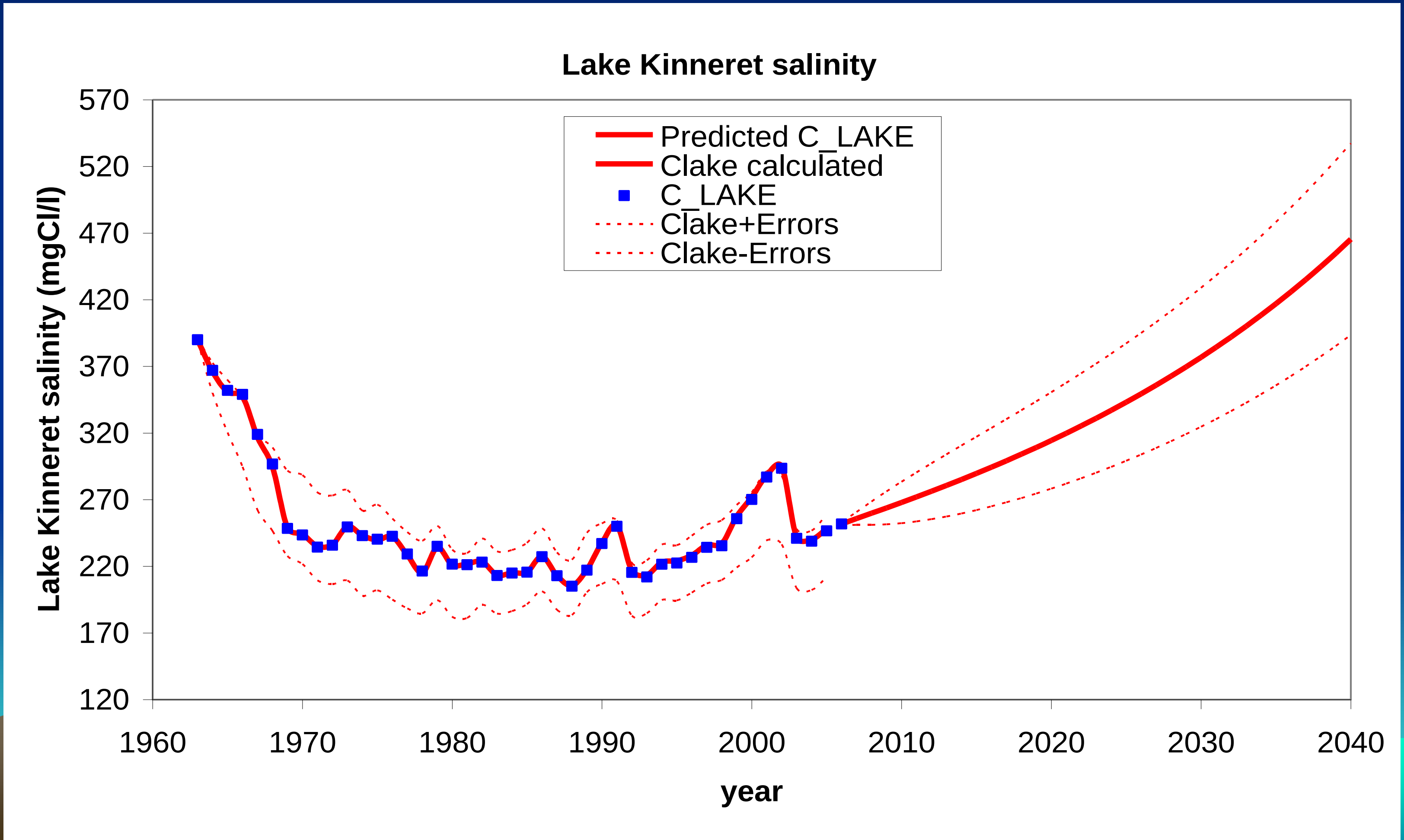
Conclusions

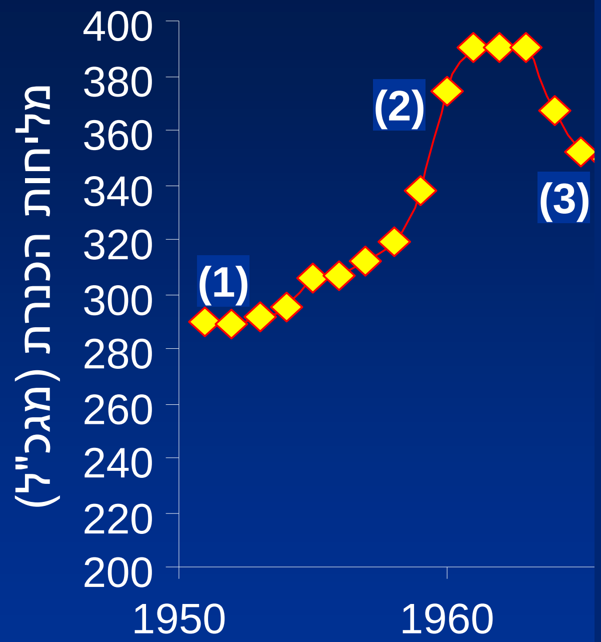
- Salinity changes are the full lake salinity response to both gradual reduction in water inflows and step reduction of solute inflows
- Since the middle of the 1980s a slow increase in lake salinity is observed as a result of reduced amount of inflows (and outflows).
- During the the 1980s the influence of the reducing water inflows became more significant than the effect of the step reduction of solute, 20 years earlier.
- We are now witness of the gradual increase of lake salinity due to the continuous reduction of inflows



Predictions of future lake salinity: Example

- The salinity of the lake is expected to increase significantly if reduction of inflows will continue





The historic record of lake salinity during 1950-1964

1. **During the years 1954-1962 significant increase.**
2. **Between 1961-1963 reaching peak values of ~390 ppm Cl^-;**
3. **In 1964, the NWC became operative, chloride content began to drop;**

Few more questions

- Why Lake Kinneret salinity increased during the 1950?
- How it is connected to the LSM theory?
- How it is connected to the "Red Line" policy?

Why Lake Kinneret salinity increased during the 1950?

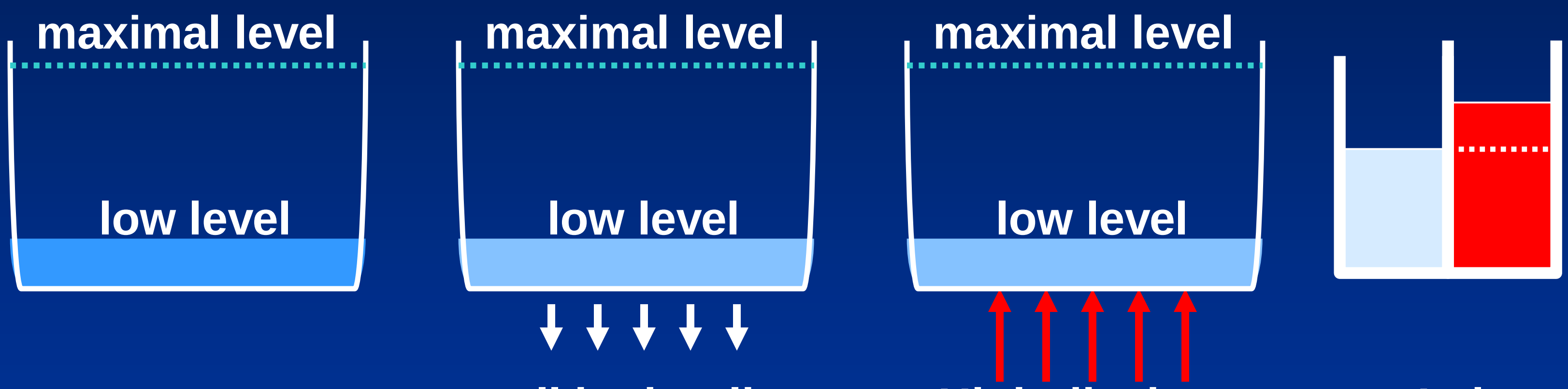
Various academic references noted that the 50's and beginning of the 60’s were relatively dry, and therefore relatively little fresh water reached the a lake and caused increased salinization.

Is this a complete explanation?

Calculations from 1 October 1954 to 1 October 1962 suggest additional solute inflows during this period. From solute balance calculations, it is possible that during this 8-year period, the input of solutes to the lake increased to an annual average of ~ 168,000 t of Cl^-, i.e., 8,000 t higher than any calculated average measured since 1960 (see details in the solute balance section).

Lets test the LSM and GFM through the eyes of the decision makers at that time:

Self potential model (SPM)

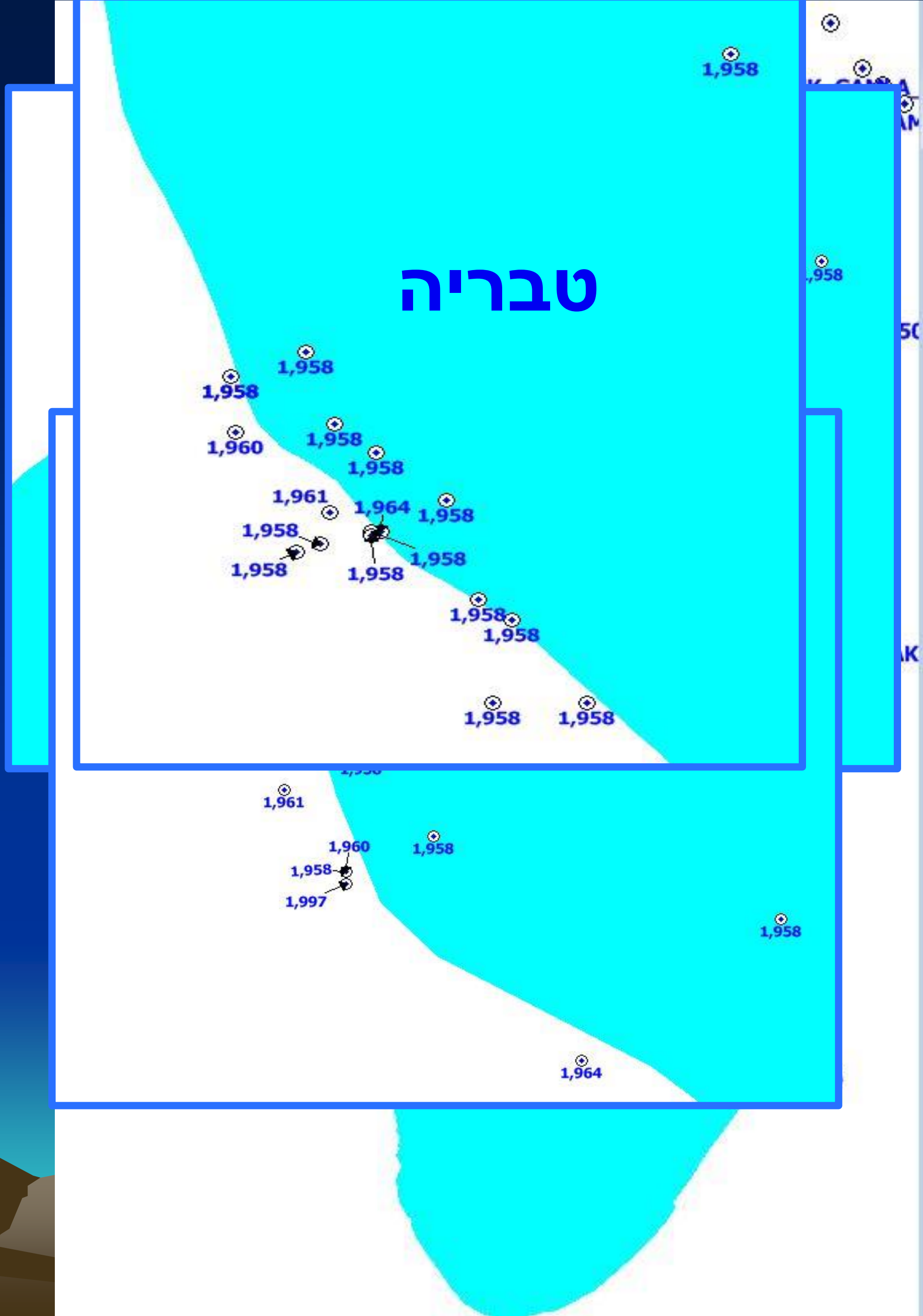


low lake level → **small hydraulic pressure on the brine** → **High discharge from saline springs** → **Lake Salinity increase**

All conditions to support the SPM were filled: low lake level, relatively high solutes flow, and increasing salinity! Conclusion: The lake level drop should be limited in order to prevent increased solutes input – a **red line** is required!

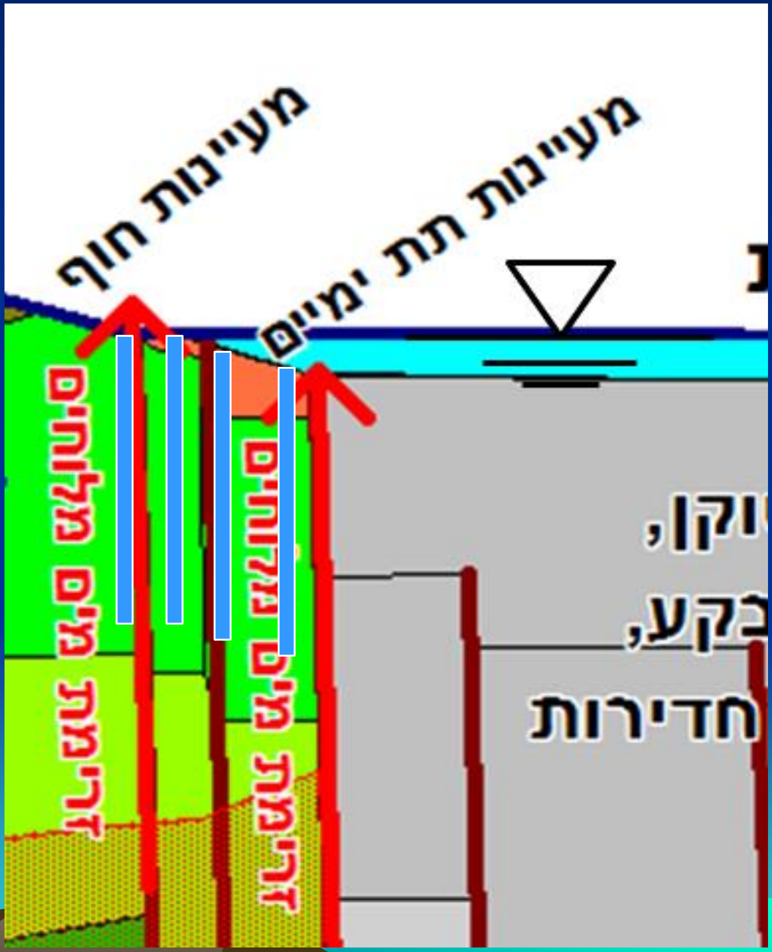
However,

During the 1950s, the State of Israel carried out intensive research on the Lake Kinneret salinity, in preparation to develop and operate the NWC. As part of this research effort, at least 60 new boreholes (IHS database) were drilled in the region of the west coast of the lake, from which at least 28 boreholes were drilled offshore in the bottom of the lake.



What was the result of drilling dozens of wells in and around the Lake Kinneret?

Massive drilling during the 1950s resulted in a temporary disturbance to the steady hydrological system of the lake-aquifer and a temporary increase in solute flux to the lake (~ 2,000 t Cl^- per offshore borehole). The effect of these boreholes faded throughout the years after they were abandoned, artificially blocked, or clogged by natural sedimentation in the lake.



Summary

- Since the operation of the “National Water Carrier” in 1964, the Lake Kinneret salinity causes major environmental problem. The following two aspects were discussed:
- **Description of the case study:** (1) the lake salinity as a source of solute export by the Israeli water supply system; (2) the hydrogeological causes for lake salinity; (3) history of salinity measurements;
- **Management and operational aspects:** (1) the proposed mechanisms of lake salinization, and the determination of ‘red line’ policy to ensure minimum allowed lake level; (2) a complete mixing type model to predict the future salinity of the lake; (3) summary of the current knowledge and operation of Lake Kinneret salinity. (4) Is there a justification for the ‘red line’ policy from the salinization point of view?

Lake Kinneret salinity in peer reviewed journals (incomplete list)

- Abbo H, Shavit U, Markel D, Rimmer A (2003) A Numerical Study on the Influence of Frac-tured Regions on Lake/Groundwater Interaction; the Lake Kinneret Case. Journal of Hydrology, 283/1-4 pp 225-243
- Assouline S (1993) Estimation of lake hydrologic budget terms using the simultaneous solution of water, heat, and salt balances and a Kalman filtering approach - app
- Berg ... nd Water 36: 409-417
- Gold ... ctromagnetic (TDEM) geophysical technique. Israel Journal of Earth Sciences. 53: 187-197
- Gvirtzman H, Garven G, Gvirtzman G (1997) Hydrogeological modeling of the saline hot springs at the Sea of Galilee, Israel. Water Resources Research, 33(5): 913-926
- Hurwitz S., Goldman M, Ezersky M, Gvirtzman H (1999) Geophysical (time domain electro-magnetic model) delineation of a shallow brine beneath a freshwater lake. The Sea of Galilee, Israel. Water resources research, 35, 3631-3638
- Hurwitz S, Lyakhovsky V, Gvirtzman H (2000a) Transient salt transport modeling of a shallow brine beneath a fresh water lake, the Sea of Galilee. Water Resources Research, ...
- Hurwitz S, Stanislavsk ... ctions in a continental rift: Sea of Galilee, Israel. Geological Society of America Bu...
- Issar AS (1993) Recha ... ental Geology, 21, 152-159
- Katz A, Nishri A (2013 ... Lake Kinneret (Sea of Galilee), Israel. Geochimica et Cosmochimica Acta 1...
- Klein Ben-David, Saas ... s: The Jordan-Dead Sea Rift valley. Geochimica et Cosmochimica Acta 68:...
- Kolodny Y, Katz A, Starinsky A, Moise T, Simon E (1999). Chemical ... sources in Lake Kinneret (Sea of Galilee), Israel. Limnology and Oceanography 44:1035-1044
- Mazor E, Mero F (1969) Geochemical tracing of mineral resources in th... basin, Israel. J. Hydrol, 7:276-317
- Mero F (1978) Hydrology, In: C. Serruya [Ed.], Lake Kinneret, Monograph... Dr. W Junk, pp. 88-102
- Mero F, Simon E (1992) The simulation of chloride inflows into Lake Kinne... 138: 345-360
- Nishri A, Stiller M, Rimmer A, Geifman Y, Krom M (1999) Lake Kinneret, The ...e): The effects of diversion of external salinity sources and the probable chemical composition of the internal salinity sources. Chemical Geology 158: ...
- Rimmer A (2000) The Influence of lake level on the discharge of the Kinneret sal...s. Advances in Limnology. 55:55-67
- Rimmer A (2003). The Mechanism of Lake Kinneret Salinization as a Linear Reserv... nal of Hydrology, 281(3):177-190.
- Rimmer A (2007) System approach hydrology tools for the Upper Catchment of the ... River and Lake Kinneret, Israel. The Israel Journal of Earth Science. 56:1–17
- Rimmer A, Gal G (2003) The saline springs in the solute and water balance of Lake Kinn... Israel. Journal of Hydrology, 284(1-4):228-243
- Rimmer A, Hartmann A (2012) Simplified conceptual structures and analytical solutions f... oundwater discharge using reservoir equations. Chapter ...0 in InTech Open Access book, "Water Resources Management and Modeling", ISBN 978-953-5...246-5
- Rimmer A, Aota Y, Kumagai M, Eckert W (2005) Chemical stratification in thermally stratified ...es: A c... lance model. Limnol. Oceanogr. 5... 47-157
- Rimmer A (2007). System approach hydrology tools for the Upper Catchment of the Jordan Riv... el. The Israel Journal of Earth S...nce. 56: 1–17.
- Rimmer A, Givati A, Samuels R, Alpert P (2011) Using ensemble of climate models to evaluate futur... urnal of Hydrology 410:248–259.
- Rimmer A, Hurwitz S, Gvirtzman H (1999) Spatial and temporal characteristics of saline springs: Sea o...
- Simon E, Mero F (1992) The salinization mechanism of Lake Kinneret. Journal of Hydrology, 138: 327-343
- Starinsky A (1974) Relationships between Ca-chloride brines and the sedimentary rocks in Israel. PhD thesis. The H... ew: English Summary).
- Stiller M (1994) The chloride content of pore water of Lake Kinneret sediments. Israel Journal of Earth Sciences 43:179-...
- Stiller M, Carmi I, Munnich KO (1975) Water transport through Lake Kinneret sediments traced by tritium, Earth Paler... :297-304
- Stiller M, Rosenbaum JM, Nishri A (2009) The origin of brines underlying Lake Kinneret. Chemical Geol...
- Rimmer, A. and A. Nishri, 2014. “Salinity” Chap. 8 in “Lake Kinneret – Ecology and Management”.Zohary T., S... inger, Heidelberg.

Thank you