to Eric Alvarez, from M. R.

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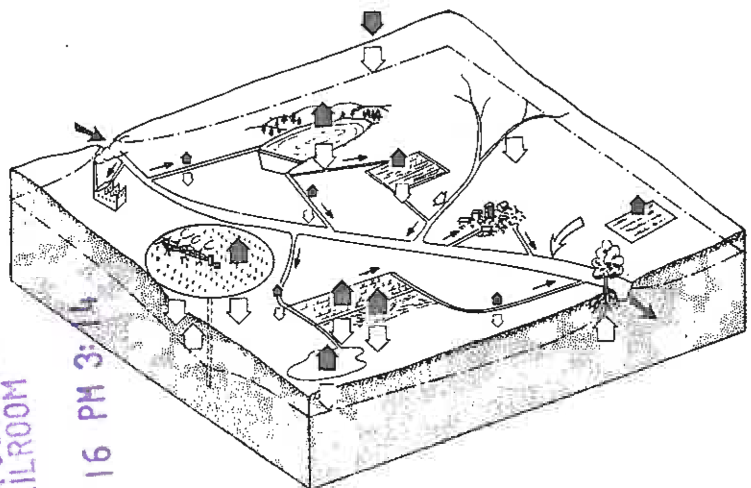

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Jorge A. Ramirez

No Runoff, No habitat, No any resources

The Agonizing San Francisco Bay Ecosystem

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Abstract

Cumulative effects of the impoundment of the San Francisco Bay watershed have resulted in chronic depletion of spring runoff and an anomalous high frequency of occurrence of subnormal wetness that contributed greatly to the deterioration of the Bay system. This has triggered an accumulation of entropy that has adversely affected species diversity, migration patterns and spawning and, has led to precipitous decline fish and shellfish. Two major failures have exacerbated the detrimental effects of excessive impoundment, namely: (1) water planning is based on Four River Index (Sacramento River basin) only, though the Delta and Bay were shaped over millennia in the combination with the San Joaquin river basin and (2) the Laws of Thermodynamics have been ignored as well as ecosystem tolerance and limitations to diversions beyond which entropy tends to reach maximum (the magnitude of these diversions and their affect on fish, which encompassed nearly 60 years is discussed in great details in Rozengurt et al., 1987a,b).

1. River-coastal sea continuum.

Historically, unobstructed runoffs and its exchange with estuaries, and adjacent coastal seas (for example, the San Francisco Bay and Gulf of Mexico estuaries, and others) maintained their rather intricate, quasi-equilibrium mechanism and rates of their interaction during seasons and years. Therefore, it is logical to expect that the predominant ranges of unimpaired runoff are responsible for developing in the San Francisco Bay of four major, estuarine regime-sustaining features, namely: (1) ecological continuum of the river into adjacent, coastal sea; (2) predominance stochastic variables of rivers' flows from entirely watersheds; (3) a quasi-dynamic equilibrium of the Bay; and (4) limited biochemical resilience and tolerance of the Delta - Bay ecosystem's biota against prolonged disturbances, especially man-induced droughts (due to dewatering). The following is a brief explanation of these properties:

First. The Bay (estuary) may be conceptually perceived as an evolving ecological continuum of two rivers into an adjacent coastal sea that is

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maintain foremost by renewable, but limited runoff. At any given time, the kinematic energy of runoff tends to preserve the estuary through the balancing exchange of a certain ratio of properties of fresh, brackish, and marine water masses (Table). In general, unimpaired interaction of water masses sustained the balanced exchange of deltaic and estuarine properties. These processes maintained specific continuum of five interactive zones (Venice International classification of 1958): delta, avant-delta, intermediate, brackish, and salty water. Each zone is defined by increasing ranges of salinity from fresh to marine water. This natural interaction, typical for any estuaries, particularly during the late winter - spring flooding, determines for year(s) the Bay' richness, vitality, and survival. But today, the cascade of dams in the Sacramento and San Joaquin rivers' watersheds and water conveyance facilities in the Delta, and beyond, like the Central Valley Project (CVP, since 1930s) and State Water Project (SWP, since 1950s) put the end of a natural continuum in the name of essential progress the State of California. As such, despoliation of the Delta - San Francisco Bay and adjacent coastal ecosystem has occurred. Despite that water management is planning to withdraw more water to produce a mesophytic agricultural environment in a semi-desert region. This will further impede continuum and functioning of Sacramento - San Joaquin Rivers - San Francisco Bay and the adjacent coastal sea.

Second. The distribution of precipitation (snow and rainfall) over watersheds coupled with climatological properties determines the monthly, seasonal, and annual runoff fluctuations whose volumes are the core for stochastic analysis and the classifications of wetness of a year. Current planning water distribution among different users in California is based on a water year-type classification called the Four-River Index (**FRI**, the sum of unimpaired runoff of the four major rivers in the Sacramento River basin; MAF – million acre-feet) whose a perennial **FRI*** = **17.2** MAF; 1921-1978). But the **FRI*** accounts for only 61% of the average of the combined Sacramento - San Joaquin River inflow to the Delta, while the norm of natural river inflow the rivers' watersheds for the same period was equal, **NRI** = **28.2** MAF (Rozengurt, 1987 a).

The **FRI** data base not only overlooks 25% and 100% of the Sacramento and San Joaquin river watersheds' rivers and streams, respectively, but also disregards the historical fact, namely, that San Francisco Bay geomorphological and hydrological features were molded for thousand years by blended runoffs from both. But in our case: **NRI - FRI = 9.0 MAF each year?** The questions remains, where on the Earth vanished from water balance calculation of the Bay ecosystem this stupendous amount of water? Note that according to stochastic hydrology, the analyses of perennial runoff behavior must be performed on the basis of 100% accumulating area of two river watersheds (Rozengurt, 1999). Therefore, the evaluation frequency of occurrence of years of different wetness, their classification and subsequent planning for water diversions, grounded on the FRI database, overestimates water availability in a manner incompatible with science of hydrology or the relatively meager natural runoff. It follows that in normal, and especially in

sub-normal and dry years, or droughts, the **FRI** classification system influences decision-makers towards permitting higher diversions (and potentially irreparably damaging the Delta and Bay ecosystems).

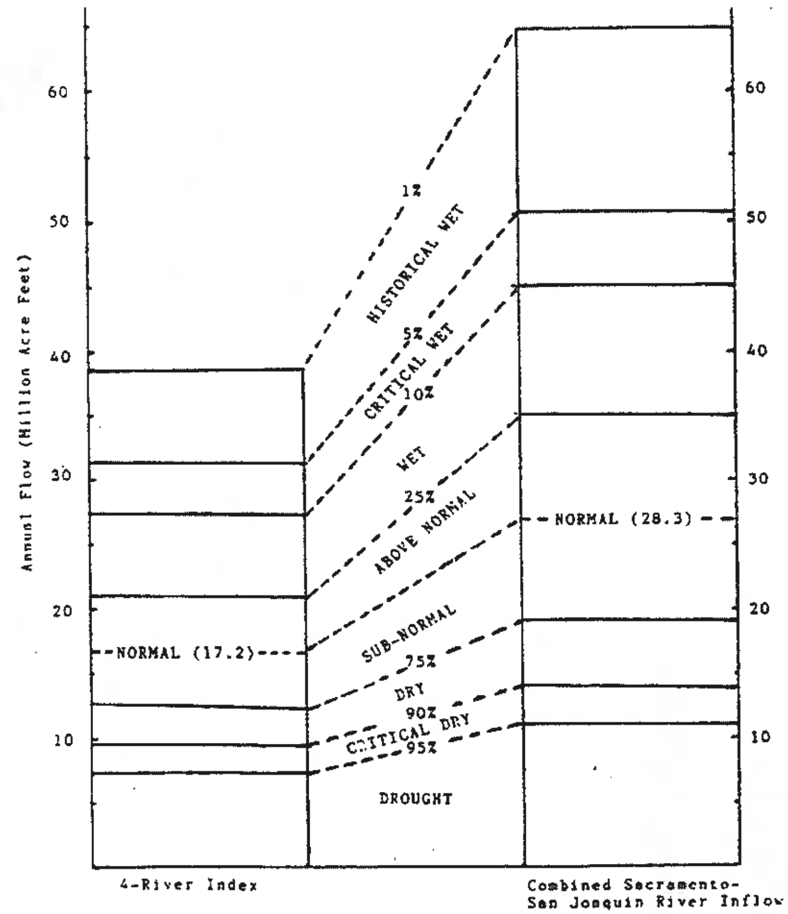

Figure 1. Comparison of Combined San Francisco-San Joaquin River Inflow and 4-River Index Water Year-Type Classification Systems (% = probability of occurrence)

Third. The frictional drag of river runoff, especially during flooding, is responsible for the seaward entrainment of volumes of estuarine waters up to 10 to 100 times greater than that of the runoff itself. The higher the unimpaired runoff, the more energy output, the stronger entrainment, vertical turbulence, mixing, and diminishing the extremes of salt intrusion and other pollutants. As such, the alteration of the potential ---> kinematic energy input/output of runoff exerts a substantial pressure on estuarine and coastal circulation (seen as a river plume and coastal hydrofront, the tint demarcation line, separating brackish and marine waters). This natural phenomenon tends to maintain a quasi-dynamic equilibrium between the Delta, Bay, and adjacent coastal zone (no diversions) suitable for the delta fresh water intakes and estuarine-dependent biota. But when this balanced coexistence has begun to falter, due to the excessive spring diversions, then long-term cumulative energy depletion occurred at an amount relatively equal to the unused energy trapped behind the dams and in water conveyance facilities. This has brought about an accumulation of entropy in the Delta and San Francisco Bay that led to their gradual despoliation (Rozengurt, 1994, 1999). Its visible indicators are: sluggish circulation, increased detention time for pollutants, salt intrusion into the delta, and loss of millions of tons of nutrients and oxygen.

It is ironic that the industrial progress forces this ecosystem "to run on entropy". This characteristic is a relative measure of unavailable amount of energy, i.e. the energy that is not capable of performing any work because this water is bound up in reservoirs. In this case, entropy gradually increases in inverse proportion to the available energy in river flow. It tends to reach its cumulative maximum in the progressive depletion of runoff. Paraphrasing the words of the Nobel Prize winning chemist, Frederick Soddy, entropy controls and determines the progression or regression of ecological, societal, and economic infrastructure, and the entire welfare of mankind. This is why costly "restoration" projects (for example, insignificant, sanitary water releases from dams in spring, or releasing of millions of fry from hatcheries) have not been effective

Fourth. There are many intimate links between living and non-living resources and hydrophysical and chemical elements of runoff. It is the fresh water that forged and strengthened the critical link between rivers and coastal seas over the past several thousand years. Estuarine resilience, tolerance, and biological self-adjustment and flourishing depends from an established range(s) of unimpaired flow fluctuations of the highest frequency of occurrence during of any month or season and natural predominant deviation of 5- years running mean from perennial norms only ± 25% to ±30%. Despite strong physiological mechanisms to ensure their survival and the highest biological productivity, even hardy estuarine living species have tolerance limits to prolonged exposure to extreme conditions, particularly of those caused directly or indirectly by **dams, diversions, dewatering, deforestation,** and **desertification**—the **5 Ds** (Rozengurt and Haydock, 1993, 1999). In addition, conversion of marshes and wetlands to cropland has exacerbated the denudation of tributaries and desertification of deltaic islands and banks. The direct origin of the **five "Ds"** is related to misguided rationale behind erroneous doctrines, which were exceptionally popular in a former Soviet Union, especially among the communist party's unscrupulous water developers.

There were four major doctrines: (1) a single-minded mentality: "Build the network of the distribution of water resources first and see what happens" and "Not one drop of fresh water should be wasted into a sea"; (2) the multiple exploit of watersheds based on purely political and/or economic grounds, considering surface (river) and ground water runoffs to be inexhaustible; (3) Deltas should be cost- effectively transformed into plumbing conduits (a kind of Peripheral Canal on the Volga Delta (Rozengurt and Hedgpeth, 1989) or other inner Delta water conveyance facilities) for local and long distance water users; avoiding the impact of hydrotechnical network on the Delta environment being of limited significance and negative development, say, levees erosions can be prevented by sand replenishment; (4) balanced optimization alternatives of watershed development and preservation of river continuum were not given equal weight in any stage of planning for impoundment.

These doctrines ignore the rules of Stochastic Hydrology and the postulates of Laws of Thermodynamics. Therefore, water management underestimated the role of river runoff, its cumulative losses of hundreds of millions of acre-feet (km^3) of freshwater and its constituents led to irrevocable despoliation of coastal ecosystems seen today (Halim,1991, Rozengurt, 1991,1992, Rozengurt and Haydock, 1993, 1994, 1999; Zaitsev, 1998). Note that the author had forecast in 1980 (the letter to the Governor J. Brown, and hundreds of copies to the Bay area and Sacramento's scientists. Rozengurt and Haydock, 1980), that if water withdrawals on the level 1977 1980 persisted, then it would take only one decade or less to arrive at the gradual degeneration of the Delta - Bay ecosystem into the basin of questionable water quality and biological productivity. The same subject was discussed in other works (Rozengurt and Haydock, 1981; Rozengurt and Herz,1981; Rozengurt et al., 1985; Rozengurt at al., 1987 a, b) and in the statement to CalFed (Rozengurt, 1998).

2. The agony of the San Francisco Bay (estuary).

The physical laws for an open estuary, i.e. having steady connection with an adjacent coastal sea through a strait, for mean sea level can be described by simple equations of conservation mass and energy. As follows from **Table 1**, the increment of salinity $\pm\nabla S_1^*$ and $\pm \nabla S_E$ may fluctuate as long as water withdrawals will continue but when the diversion at the certain value is stopped, then the new salinity of the estuary S_E^*, estuarine outflow S_1^*, and sea inflow S_2^* (equations 8-11) will tend to reach their quasi-dynamic equilibrium in a period of several years. However, if diversion starts all over again, the whole process of salt pollution of an upper estuary and Delta will be reinforced on a much higher scale. Notably, the salinity of an estuary may be slightly higher than an adjacent coastal area (eq.12). As a result, the Delta and fresh water intakes will cease to exist and be transformed into a salty swamp. Therefore, the extremely complex process of salinization of delta-estuary over the years is linked to both impoundment and cumulative losses of hundreds millions of acre-feet water (or 100s of km^3).

As result of construction of the **CVP** (Central Valley Project) and **SWP** (State Water Project) water storage (with an accumulation capacity equal to 71% of normal unimpaired runoff) and conveyance systems into and out of the Delta (15-20% of normal Delta outflow), the post-project period (since 1944) natural water supply to the Delta-San Francisco Bay has been reduced to unprecedented levels.

Since 1967, absolute values of **total diversions** with predominant range of 10 to12 MAF (or 12 km^3 – 14 km^3) per year are 2.8-3.2 times (and up to 5 times) higher than before the CVP and SWP were completed (**pre-project period of 1915-1943**). The absolute values of predominant **upstream diversion** of 6-12 MAF (or 7.2 km^3 - 14 km^3) for the post-project period were 3-5 times higher than the same for the pre-project period. The predominant range of annual **Delta diversions** since 1967 was up 4 to5 MAF (or **4.8 km^3** – 6.0km^3) and more, or almost 5 - 6 times higher than the Delta volume (1.3 MAF or 1.56 km^3); or the volume of Delta water diversions in the pre-project period.

The major cause of these persistent decreases in annual runoff is that diversions in winter (primarily upstream) range between 15 and 45% and in spring (upstream and downstream) between 30 and 80% or more of the natural water supply of the Sacramento-San Joaquin River-Delta subsystem.

Since the projects' (CVP and SWP) operations began (especially from the late 60's on), winter and spring **RRI** (regulated river inflow) to the system was reduced 1.2-1.4 and 1.6-2.4 times in comparison with mean winter and spring **NRI** (natural river inflow) to the Delta, respectively; (for 5-year running periods the prevailing range of unimpaired runoff is equal to 3-4 MAF). Therefore, for the period 1967-1992, residual winter and, especially spring **DRO** in the majority of cases corresponded to years of subnormal and below subnormal runoffs (Roos, 1992) of the **NRI** for the same period.

The pre-project period (characterized by prevalent, insignificant upstream diversion) was characterized by the highest correlations between commercial catch for a given year of the most valuable species of anadromous fish of the San Francisco Bay (Chinook salmon, Striped bass and American Shad) and average spring runoff of 2.3-3.5 MAF for the preceding 3 and 5 years, the same was obtained for annual regulated Delta outflow (**RDO**)

When in the post – project period the mean spring and annual **RDO** reached ranges of 1.0-1.5 MAF (1.2 – 1.8 km^3) and 11-15 MAF (or 13.2 km^3 to 18.0 km^3), respectively (or 27%-42% and 40%-55% of their perennial norms), a nearest quandary of deprivation of the Delta - Bay commercial and sport fishery became obvious.

Published results regarding water development in rivers entering the Black Sea, the Sea of Azov, Caspian and Mediterranean Seas in Europe and Asia all point to the conclusion that when successive spring and annual water withdrawals exceeded 30% and more than 40-50% of the of the norms, respectively, then water quality and fishery resources in the river-delta-estuary-coastal seas precipitously declined.

Commercial catches of Russian sturgeon, pike-perch, mullet, mackerel, sprat, etc., have been extinguished in the Dniester and Dnieper Estuaries - the northwestern, most productive part of the Black Sea since the late 1960's.

In the Sea of Azov (once the world's productive sea) the commercial catch of Russian sturgeon, as well as numerous other valuable semi-anadromous and anadromous fish, dropped from hundreds of thousands to several thousand tons over the last two decades due the Don and Kuban rivers impoundment. The same phenomena were observed in the Caspian Sea as well as with the commercial catch of salmon in Northern Europe.

Suffice to say that the Black-Azov Sea basin irrevocable irrigation water withdrawals since 1955 account for nearly 1,700 km^3 (three times the volume of the Sea of Azov); the Caspian Sea -1000-1,200 km^3 (this equals the North Caspian volume). At the same time, the landlocked Aral Sea ceased to exist due to immense withdrawals of runoff from two major rivers of Central Asia- Amu Darya and Syr Darya, (fresh water deficit has reached 1,300-1,400 km^3).

In the Nile Delta-Mediterranean Sea coastal zone, the commercial catch of *Sardinella* and other species have dropped from hundreds of thousands tons in the 1950's to several hundred tons since the Aswan Dam became operational (1964).

The commercial catch of striped bass in the Chesapeake Bay has declined up to 70% due to water regulation and pollution. The same percentage of fish and shellfish decline observed in the Delaware Bay and the Texas lagoons.

The impoundment of the Murray-Darling River system in Australia and construction of the salt barrier in its Delta has eliminated the fisheries in this area since the 1940's.

There are ample evidences that cumulative water withdrawals of about 600 MAF (720 km^3) from the San Francisco Bay major rivers-Sacramento and San Joaquin (since 1930s and 1910s, respectively) led to catastrophic encroachment of brackish water to the Delta. In addition, the depletion of semi-anadromous and anadromous fish catches occurred, leaving merely 1% of that of the pre- project period of construction of hundreds of large and small dams (CalFed, 2000

Despite more than $2 billion spent on evaluation and management ecosystem, the understanding necessary to preserve the Bay's health has not been achieved. Voluntaristic water planning has excluded from consideration of stochastic laws of runoff's variance and natural tendency of its limitations by climatological and geophysical properties of watershed.

The significance of this development has not been appropriately recognized or appreciated by CalFed as well of some scientific communities. Nearly 22 years ago it was determined for the Sacramento-San Joaquin rivers (Rozengurt and Herz, 1981; Rozengurt and Haydock, 1981) that when spring runoff will be maintained at one to three million acre-feet then the Delta and Bay functioning will be brought to the brink. Unfortunately, California's water management appears to be callous at that time and other time (Rozengurt, et al., 1985, 1987 a, b). Therefore, today, the Delta- Bay ecosystem have subjected immense economic and ecological penalties similar to that documented in south, semi-arid regions of the Black, Azov, Caspian sea and Aral seas' watersheds of a former USSR (Rozengurt, 1991;Rozengurt and Hedgpeth, 1989; Zaitsev, 1998). Other examples are: the Snake River/Columbia River and coastal zone; Florida's "Everglades," and Florida, Tampa, and Charlotte bays; some 40 estuaries of the Gulf of Mexico, (Halim, 1991; Simenstad et al., 1992; Rozengurt and Haydock, 1991, 1993). All attempts to restore the fisheries have failed - the current habitats have nothing in common with their teeming past.

3. Conclusion.

Large-scale impoundment of the Sacramento and San Joaquin rivers' watersheds during 1930s and 1950s has undermined unique features of river continuum into the Delta –estuary (San Francisco Bay) coastal sea and significantly hampered the ability to maintain ecological continuity suitable for indigenous living resources. . The residual runoffs are usually in disconcert, either singly or simultaneously, with water demands for fish migration and spawning versus power production and irrigation in the most vital period of the year - spring. Undoubtedly, this new, acutely negative phenomenon has eliminated alternate historical probabilities and duration of years of different wetness. With time, these non-equilibrium conditions have imposed deleterious changes on the ecosystem. Their cumulative dewatering triggered landward salt intrusion from the San Francisco Bay that contaminated the Delta water body as well as ground water tables. Salt-water invasion also fortifies abnormal. vertical density stratification leading to oxygen depletion and subsequent mass mortality of vegetation and living organism.

Sacramento - San Joaquin rivers unimpaired runoff to the Delta - San Francisco Bay over a perennial period (60 years), without dams, would be possessed the annual average norm of 28.2 MAF. But due to the impoundment, this historical amount dwindled to the average range to 2 to 12 MAF for years of different wetness (except rare observed historically wet years). Spring runoff, naturally the lifeblood of the Delta and Bay, has already dropped to 8% to 27% of what once was a norm of 11 MAF.

The frequencies and absolute values of the spring and annual deviations reach up to 40 to 85% (instead ± 25 - 30% of norms of unimpaired runoff). Since the 1960s the frequency of occurrence of years of dry, critical dry or drought-like conditions (particularly in spring) have increased up 3 to 5 times in comparison with unimpaired runoff over 55 to 100 years. Ensuing perennial water deficits have plagued river flushing and coastal rejuvenation and become chronic events of nearly global proportion. Excessive water withdrawals the Bay has deprived the Delta and Bay over 600 MAF (720 km^3) of fresh water or nearly 100 and 500 times the volume of the Bay, and the Delta; and millions of tons of organic and inorganic matter, sediment, oxygen, and etc. left behind in reservoirs and in water conveyance facilities. Today, the volumes of regulated inflow/outflows to the Bay often correspond to critical dry years or droughts from the perspective of functioning of ecosystems without dams. This systemic regime aggravation, compounded by abnormal seasonal redistribution of the **RDO** has effectively eliminated striped bass and smelt and migration and spawning salmon and other living resources of the Delta - San Francisco Bay. But due to the impoundment, this historical amount dwindled to the average range to 2 to 12 MAF (2.4 km^3 to 14.4 km^3) for years of different wetness (except rare observed historically wet years). Spring runoff, naturally the lifeblood of the Delta and Bay, has already dropped to 8% t 27% of what once was a norm of 11 MAF (12.1 km^3). The frequencies and absolute values of the spring and annual deviations reach up to 40 to 85% (instead ± 25 - 30% of norms of unimpaired runoff). Since the 1960s the frequency of occurrence of years of dry, critical dry or drought-like conditions (particularly in spring) have increased up 3 to 5 times in comparison with unimpaired runoff over 55 to 100 years. Ensuing perennial water deficits have plagued river flushing and coastal rejuvenation and become chronic events of nearly global proportion. Since 1955 due to excessive water withdrawals the Bay has deprived over 600 MAF (720 km^3) of freshwater runoff or nearly 100 500 times the volume of the Bay and nearly 500 times of the Delta; and millions of tons of organic and inorganic matter, sediment, oxygen, and etc. left behind in reservoirs and in water conveyance facilities. Today, the volumes of regulated inflow/outflows to the Bay often correspond to critical dry or droughts from the perspective of functioning of ecosystems without dams. Enormous cumulative losses of freshwater jeopardize the deltaic drinking freshwater intakes due to increase salty water intrusion. This systemic regime aggravation, compounded by abnormal seasonal redistribution of the **RDO** has virtually eliminated striped bass, shad, and smelt and migration and spawning salmon and other living resources of the Delta - San - Francisco Bay. In our view, any statement claiming that it is possible to attain some level of fish population based on questionable amount of spring runoffs less than **3 MAF** (3.6 km^3) should be considered erroneous. According to correlations of the commercial catch of anadromous fish vs. seasonal runoffs for several preceding years (Figure 2), the only way to reach a historical fish catch, one posse a historical seasonal runoff. Otherwise, according to the Second Law of Thermodynamics, the current Delta and San Francisco Bay are in a precarious condition. This will lead to the critical accumulation of entropy that signals the end of the agony for the Delta - San Francisco Bay system.

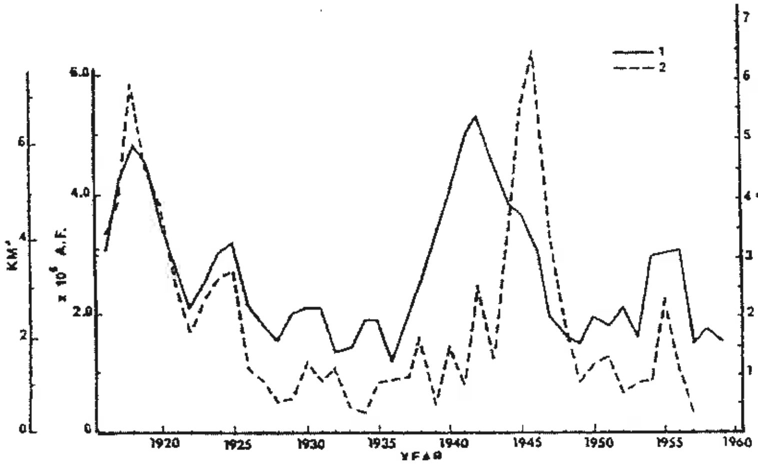

Figure 2. Relationship between (1) regulated Delta outflow for three moving months (April – May – June) and (2) commercial salmon catch in the Sacramento and San Joaquin Rivers. The salmon catch is based on a lag outflow period of 2 years; e.g., salmon catch for 1916 is based on outflow for 1912-1914.

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Table 1. The Elements Of Water And Salt Balance Of River-San Francisco Bay (Estuary)-Coastal Ecosystems

$$W_1 S_1 = W_2 S_2 \quad (1)$$

where $W_1 = (P+R)-E+W_2$ (2)

Where: **P** - precipitation; **R** - runoff, **E**- evaporation; **N**- balance;

or $W_1 = N + W_2$

W_1 = the estuarine outflow, W_2 - the sea inflow;

$$S_1 = \frac{W_2 S_2}{W_1} \quad (3)$$

S_1 and S_2 - salinity of an estuary outflow and sea inflow; S_E - salinity of the estuary;

T - retention time (month, year);

V-- vol. of an estuary (equations 1-7).

$$S_E = f(R, S_1) \quad (4)$$

$$W_1 = N/(1 - \frac{S_1}{S_2}) \quad (5)$$

$$W_2 = N/(\frac{S_2}{S_1} - 1) \quad (6)$$

S_1^* and S_E^* an accumulative salinity of an estuary in the case cumulative runoff depletion (e.g., 8 & 9);

The equation 10 for impaired runoff.

$$T = (1 - \frac{S_1}{S_2})V/N \quad (7)$$

"**n**" = an amount of years of salt accumulation in the Delta-Bay ecosystem;

$$S_1^* \Big|_{i=1}^{n} = S_1 \pm \Delta S_1^* \quad (8)$$

ΔS_1^* and ΔS_E^* are accumulative increment of salt for i = 1, 2, 3... "**n**" years.

$$S_E^* \Big|_{i=1}^{n} = S_E \pm \Delta S_E^* \quad (9)$$

If the runoff **R** = O or less **P-E** then equations 11 underscored the cause substantial increase salinity of estuarine waters (12).

$$W_1^* S_1^* = W_2^* S_2^* \quad (10)$$

$$W_2^* > W_1^* \quad (11)$$

$$S_2^* \geq S_E^* \geq S_1^* \text{ and } S_1^* \approx S_2^* \quad (12)$$

In this case, the entropy will tend to reach stabilized maximum and estuarine properties will be transformed into an artificial harbor where S_1^* S_2^*