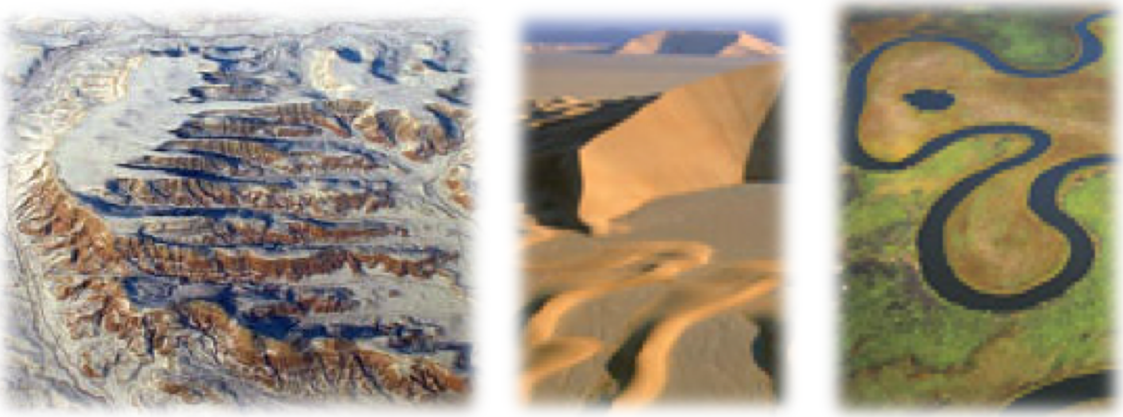
457.562 Special Issue on River Mechanics (Sediment Transport)

.17 Reservoir Sedimentation



Prepared by Jin Hwan Hwang

Intro

- Today an increasing number of dams are reaching the end of their “design life” and their operation is increasingly affected by long-term sedimentation issues ignored at the time of construction.
- Dam sites are limited and irreplaceable.
- But, when sedimentation is controlled, dams can have useful lives greatly exceeding any other type of engineered infrastructure.

Intro

- Issues related with sedimentation in reservoirs
  - Continuation of reservoir operation beyond the original design life despite sediment accumulation
  - Modification of existing structures and operating rules to minimize sedimentation impacts
  - Design and management of new reservoirs to minimize sediment accumulation
  - Dredging and other sediment removal techniques
  - Sediment impacts associated with dam decommissioning and removal
  - Sediment management to minimize or mitigate environmental impacts.

Sedimentation rates

- Sedimentation rate is expressed as of the percentage of total original reservoir volume lost each year.
- Crowder (1987) estimated the rate of storage loss in the US at 0.22% per year.
- Dendy et al. (1973) showed that storage loss tends to be more rapid in smaller reservoirs than in larger ones due to generally higher capacity: inflow ratios and lower specific sediment yields in the latter.
- The rate of storage loss in other parts of the world is generally higher than in the US, and Mahmod (1987) estimated that storage capacity worldwide is being lost at an annual rate of 1%.

Reservoir Half-Life

- Reservoir life is computed by dividing total reservoir volume by annual sedimentation volume during the early years of impoundment, thereby estimating the number of years to completely fill the reservoir.
- Reservoir half life is the time required to lose half the original capacity to sedimentation is thus a much better approximation of when sedimentation problems will become truly serious.
- Loehlein (1999) describes problems including hindered floodgate operation and clogging of hydropower and water supply intakes due to sedimentation at several flood control reservoirs in Pennsylvania, with only 6% storage loss.

Reservoir Life

- Reservoir life has traditionally been conceptualized based on the continuous filling of the usable storage pool, presumably followed by abandonment of the structure.
- Three stage
  - (stage 1) Continuous sediment trapping: During the first stage of reservoir life, continuous sediment trapping occurs during all inflowing flood events. A cross section perpendicular to the axis of the reservoir in continuously impounded areas will reveal a depositional sequence that fills the deepest part of the cross section first, eventually producing sediment deposits that are essentially flat.

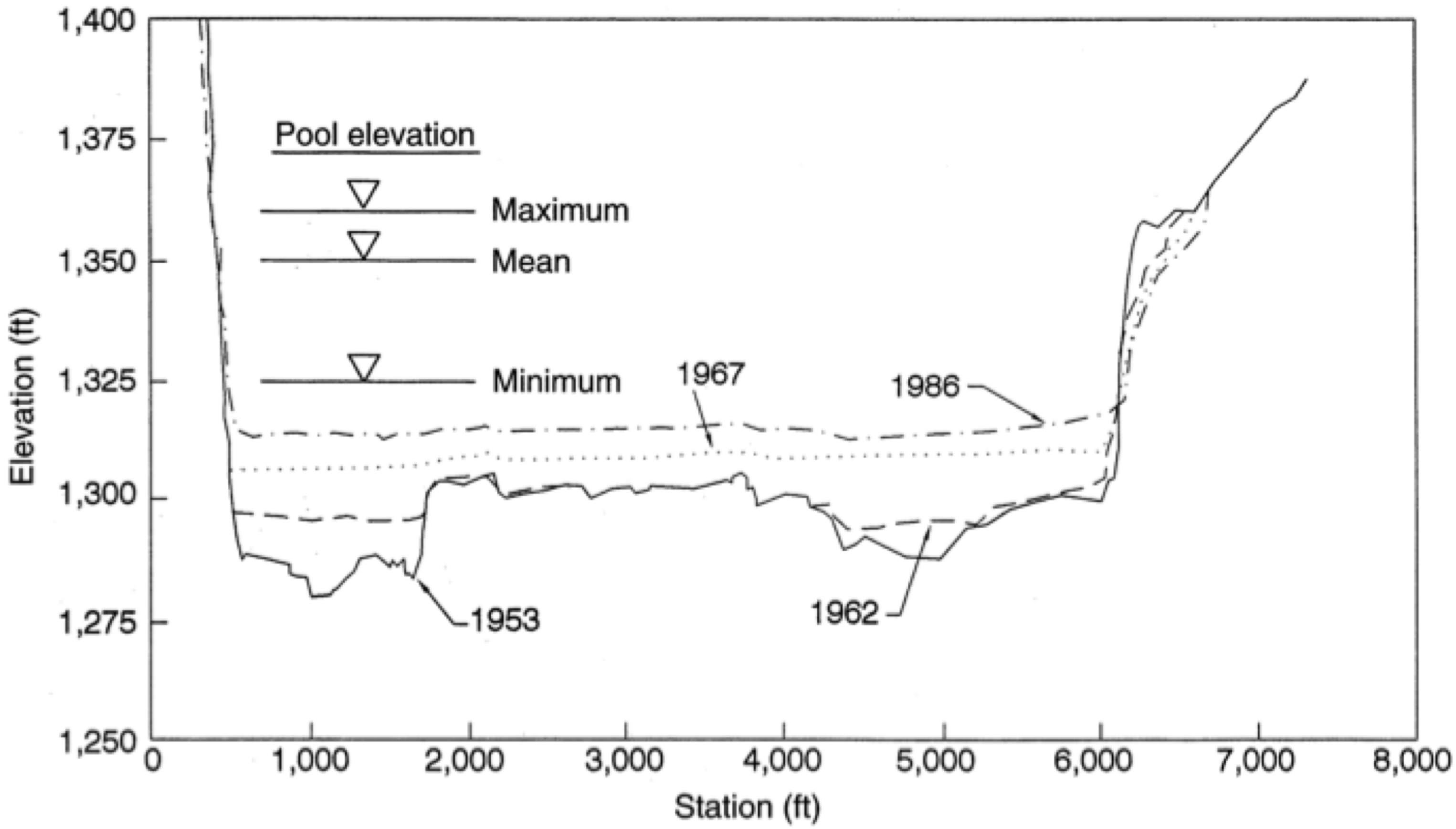
Reservoir Life

- (stage 2) Partial sediment balance: During the second stage, the reservoir transitions from a continuously depositional environment to a mixed regime of deposition and removal
- If sedimentation is allowed to proceed uninterrupted, the reservoir at this stage will become largely filled with sediment and a channel-floodplain configuration will develop in the former pool area.
- The inflow and discharge of fine sediment may be nearly balanced but coarse bed material continues to accumulate. Sediment management techniques, such as drawdown to pass sediment-laden flood flows through the impounded reach or periodic flushing, can produce a partial sediment balance to help preserve useful reservoir capacity.

Reservoir Life

- (stage 3) Full sediment balance: A long-term balance between sediment inflow and outflow is achieved when both the fine and the coarse portions of the inflowing load can be transported beyond the dam or artificially removed on a sustainable bases.
- However, sediment movement through the impoundment condition because sediment may accumulate during smaller events and be washed out during large floods or may be removed at intervals by dredging or flushing.

Reservoir Life

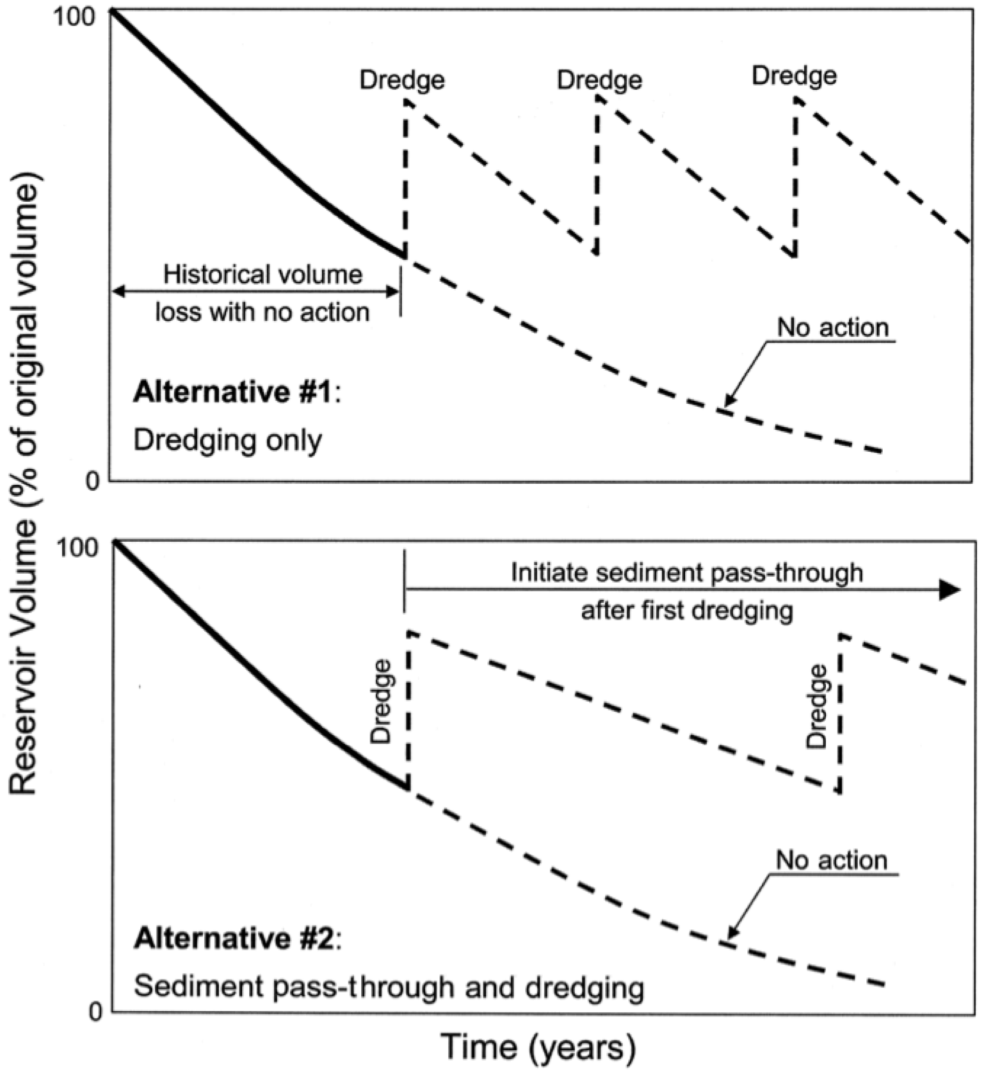


- Lake Francis Case on Missouri River above Ft. Randall Dam

Capacity-History Curves

- Reservoir volumetric capacity will steadily diminish in a reservoir that is continuously impounded, although the rate of storage loss will tend to decrease as the reservoir’s hydrologic size and trap efficiency diminish.
- Capacity-history curves may be drawn to illustrate historical and anticipated changes in usable storage volume under different management options.

Capacity-history curve



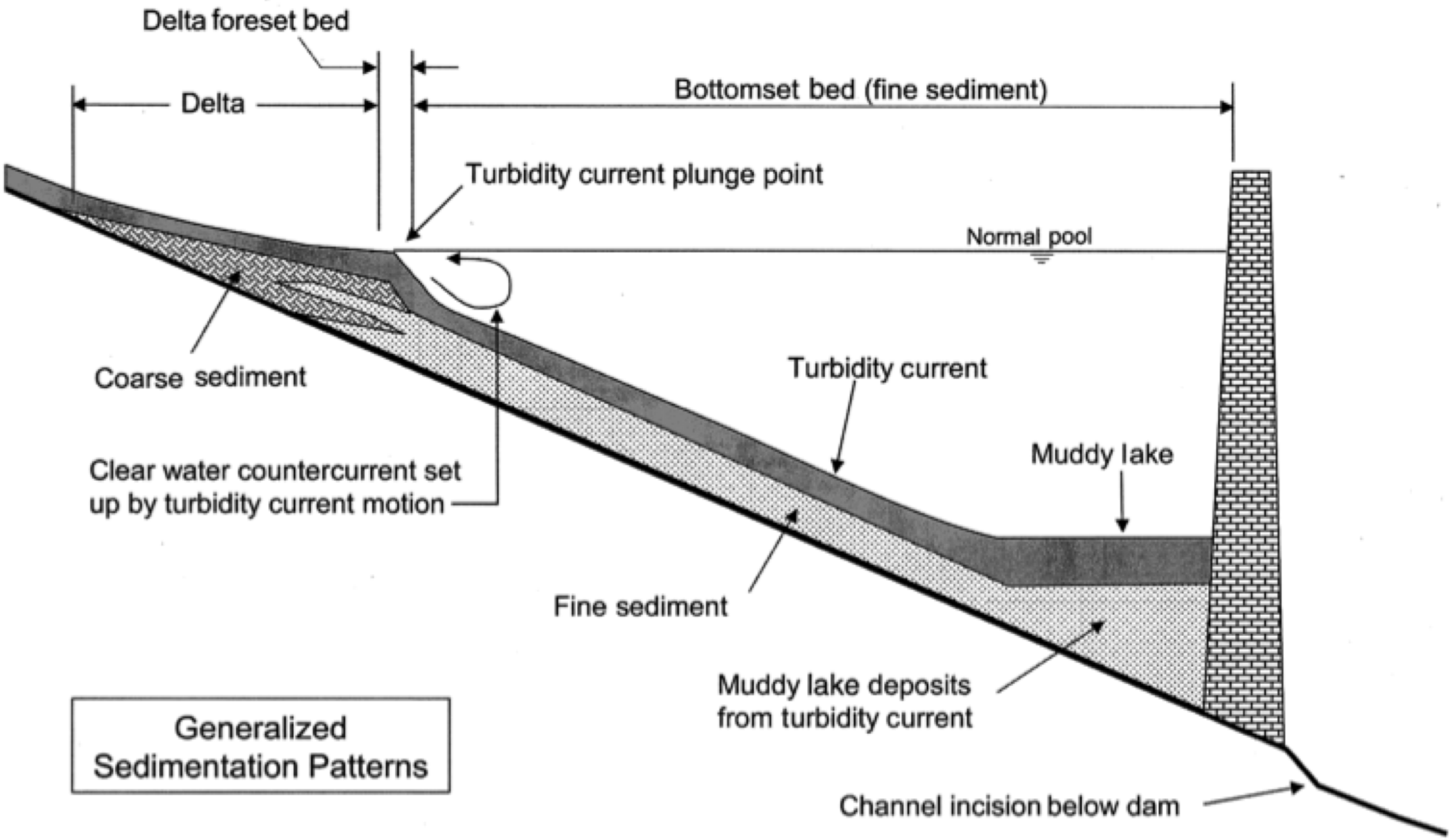
Sediment Impact

Sedimentation Impacts

Above Normal Pool:
Bed aggradation, flooding, higher groundwater levels, impaired navigation

Pool Area:
Reduced conservation and flood control pool volumes, clogging of intakes

Below Dam:
Channel incision, bank erosion, lower groundwater levels, loss of bed-load inputs and bed armoring



Generalized Sedimentation Patterns

Sediment delivery to reservoirs

- Sediment yields vary remarkable over time and space
- This variability must be understood to properly interpret data, to predict sediment yields, and to successfully implement strategies for reducing sediment inflow or passing sediment laden flows around or through the storage pool.

Erosion and sediment yield

- Erosion rates from farms and watersheds are computed by empirical models,
  - the Universal Soil Loss Equation (USLE) and its variants (MUSLE, RUSLE)
  - More complex physically based detachment and transport models, such as AGNPS, ANSWERS, CREAMS, SEDIMONT, and WEPP
- Sediment yields:
  - Is the amount of sediment transported beyond or delivered to a specified point in the drainage network over a specified time period.
  - Always lass than and typically much less than the amount of sediment eroded within a watershed due to redeposition prior to reaching stream channels or reservoirs

Erosion and sediment yield

- Sediment delivery ratio
  - Ratio of eroded sediment to delivered sediment.
  - Because erosion rates are computed rather than measured, the sediment delivery ratio is actually the ratio of computed erosion to measured yield.
  - Sediment yield estimates derived from erosion estimates are typically more sensitive to errors in estimating the sediment delivery ratio than to errors in erosion rate.
  - For example, with a sediment delivery ratio equal to 10% of erosion, a 1% error in estimating sediment delivery ratio would have the same impact on computed sediment yields as a 10% error in the erosion estimate.

Quantifying sediment yield

- Estimating sediment yield by reservoir survey
- There are two basic strategies for measuring sediment yield
  - By the volume of sediment deposited in reservoirs
    - More accurate since reservoirs collect sediment from all events since their construction, eliminating problems of missed or underreported events at fluvial gauge stations.
    - Revealing patterns of sediment deposition critical to evaluating remedial actions.
    - But nor reveal the spatial or temporal patterns of sediment delivery needed to analyze some sediment management alternatives.
  - Continuous monitoring of fluvial sediment discharge

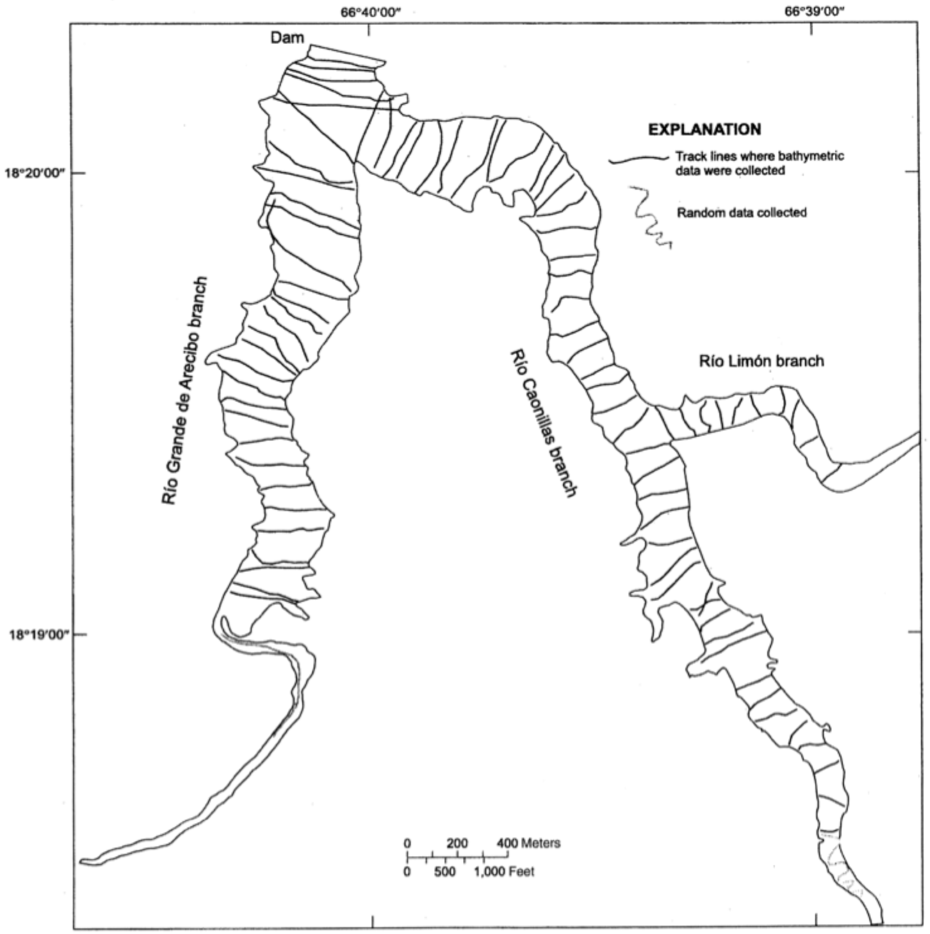
Quantifying sediment yield

- Bathymetric survey
  - Successive reservoir surveys are used
    - to track volume depletion and revise elevation-capacity curves;
    - to predict the type, magnitude and time horizon for sedimentation problems
    - To calibrate mathematical models of sedimentation
    - To help develop and monitor the effectiveness of sediment management practices.
  - For modeling of sedimentation processes, bathymetric mapping should be complemented with borings to determine the grain size of the deposits and verify estimates of deposit bulk density determined by empirical methods.

Quantifying sediment yield

- Bathymetric survey
  - Successive reservoir surveys are used
    - to track volume depletion and revise elevation-capacity curves;
    - to predict the type, magnitude and time horizon for sedimentation problems
    - To calibrate mathematical models of sedimentation
    - To help develop and monitor the effectiveness of sediment management practices.
  - For modeling of sedimentation processes, bathymetric mapping should be complemented with borings to determine the grain size of the deposits and verify estimates of deposit bulk density determined by empirical methods.

Quantifying sediment yield



- Contour surveying line
- Determine the volume of reservoir or sediment.
- Through this, we can compute average specific sediment yield ($tn/km^2/yr$)

Quantifying sediment yield

- Effective watershed-year : the changing area of the watershed effectively contributing sediment

$$\begin{pmatrix}\text{Effective}\\ \text{watershed}\\ \text{years}\end{pmatrix} = \left[\begin{pmatrix}\text{Unregulated}\\ \text{area}\end{pmatrix} + \begin{pmatrix}\text{Regulated}\\ \text{area}\end{pmatrix} \times \begin{pmatrix}\text{Sediment}\\ \text{Release}\\ \text{Efficiency}\end{pmatrix}\right] \times years$$

- Where the sediment release efficiency = 1- trap efficiency for upstream reservoirs.

Quantifying sediment yield

- Deposited thickness over event horizons
- Lacking reliable original bathymetric data, sediment thickness over a datable horizontal can be used to determine sedimentation rate.
- Cesium 137 :
  - manmade isotope. (nuclear weapons testing). It is tightly sorbed onto clay particles and penetrates only a short distance into clayey soils.
  - Half-life of 30 years.
  - Mark radioactive horizons corresponding nuclear weapons testing.
  - Determine sedimentation depths overlying this event horizon both in reservoirs and in natural lakes.

Quantifying sediment yield

- Sediment depths over the density horizon corresponding to the original bottom can also be determined by a subbottom profiler
  - Higher frequency (200 MHz) sonar signal for bathymetric mapping in combination with a lower-frequency signal (4-28MHz)
  - The lower frequency signal penetrates finer sediment and is reflected from underlying denser layers corresponding to the original bottom, allowing the sediment thickness to be mapped.

Sediment yield estimation from fluvial data

- Sediment rating curves
  - Fluvial sediment load is determined by the product of stream-flow and discharge-weighted sediment concentration.
- Sediment load is usually computed from a long-term discharge record and a sediment rating curve that relates concentration to stream flow.
- The large floods or hurricane events responsible for much sediment transport may be represented by very few data points.

Sediment rating curve

- Relation between water discharge and suspended-sediment concentration for the Missouri river at Hermann, Holmes 1993)