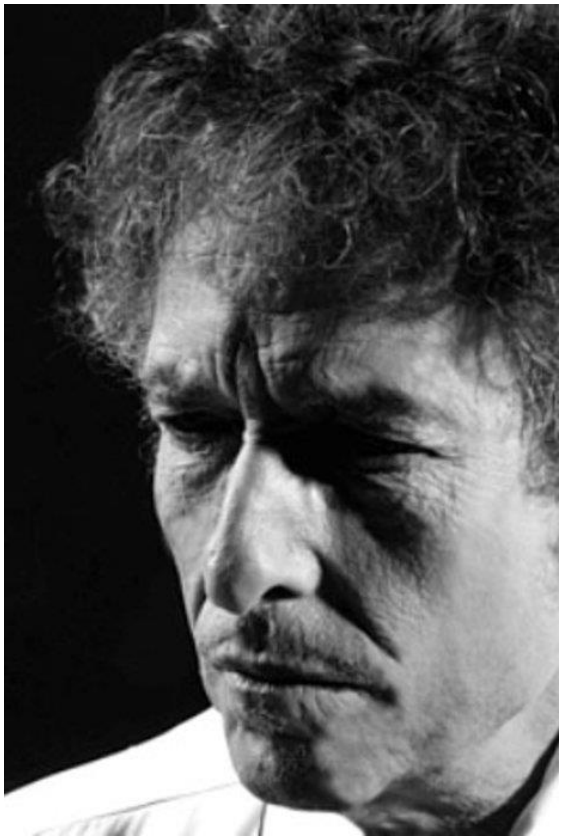
The Times They Are a-Changin’

He won the Nobel Prize for Literature. If you enjoy his thinking, you may conclude that he should have been awarded the Nobel Prize for Science as well.



Come gather 'round people
Wherever you roam
And admit that the waters
Around you have grown
And accept it that soon
You'll be drenched to the bone.
If your time to you
Is worth savin'
Then you better start swimmin'
Or you'll sink like a stone
For the times they are a-changin'.
Come writers and critics
Who prophesize with your pen
And keep your eyes wide
The chance won't come again
And don't speak too soon
For the wheel's still in spin
And there's no tellin' who
That it's namin'.
For the loser now
Will be later to win
For the times they are a-changin'.

(1964)

Dylan was prescient. He saw it coming.

How we judge the safety of dams has been conditioned, among other things, by epistemic uncertainty in our approaches to estimating flood and earthquake loads. We predict flood and earthquake loads on the basis of what happened in the past. There are limits to knowledge that affect our ability to evaluate dam safety. Epistemic uncertainty is our constant companion, and our predictions about extraordinary events rely on our knowledge of the past. In that regard, we are prisoners of history. The waters have grown.

Think back to Carroll's 1872 classic Through the Looking Glass. The White Queen scolds Alice for not remembering to eat jam only on Thursday. To which Alice replies: "It's not Thursday. I can't remember things before they happen." To which the queen retorts: "It's a poor sort of memory that only works backward."

That's the memory we have. Flood and earthquake predictions look backward to estimate what might lie ahead, but they do not capture the randomness of nature. The engineer making judgments about a dam's safety relies upon estimates by experts specializing in hydrology and seismicity. Analyses to derive loading estimates involve independent variables that affect the outcomes. There often is disagreement among experts about what the loading estimates should be. Nature regularly provides surprises that exceed prior estimates. Or centuries may pass without loads approaching predictions. We simply don't know what we don't know.

Knowledge about how the earth behaves is improving. We are coming to understand changes in magnitude and duration that will drive our future estimates of flood and earthquake loading. They will not be our past estimates.

For the times they are a-changin'.

We'd better start *swimmin'*.

Changes will be the consequence of a single initiator – global warming. Warming has the effect of moving weight from land into the oceans as it melts the ice covering large portions of land. Estimates of that weight shift are expressed in gigatons and already there have been thousands of gigatons shed from land to ocean. That movement affects the earth's isostasy and will affect future loads on dams.

Put more weight in the ocean and the ocean bottom sinks and the surrounding land masses rise. The effect can be long lasting. For example, Iceland and northern Europe still are rising from the melting of Pleistocene ice that may have been thousands of feet thick ten thousand years ago. Isostasy works to keep it all in balance but the shift of weight

causes basic changes. Global warming is responsible for the melting, sea level increase, and ocean temperature change that then affect the earth's rotational speed and direction of the earth's axis. The earth continues to adjust to these changes to preserve equilibrium, potentially affecting hydrology and tectonics.

The consequences of the weight shift range from simple to complex.

- Oceans rise
- Ocean floor sinks
- Land rises
- Stream flows decrease from loss of flow from glaciers
- Extreme weather increases, e.g. Harvey
- Earth's axis of rotation migrates
    - Earthquakes (the Tohuku earthquake is estimated to have shifted the earth 4 inches on its axis.)
    - Ocean temperatures rise
    - Mantle adjusts to weight re-distribution
- Earth's magnetic poles migrate to adjust to polarity changes within the core.
- Earth's rotational speed slows down from concentrations of weight such as Three Gorges reservoir (~42 billion tons) and dams worldwide
- Or speeds up from melting glaciers and the resulting shift in underlying mantle responding to weight re-distribution.

Shifting of mantle may have allowed concentrations of patches of magnetic field from the core to shift causing the earth's magnetic field to migrate.

Contribution of melting glacial ice from land to stream flow will diminish.

Rising ocean and atmospheric temperatures will cause a rapid rise in melting of glaciers – causing sea level to rise. The Thwaites is a massive glacier in the Antarctic about the size of Florida. If it becomes unstable and detaches from the land, melting will accelerate, and sea level will rise rapidly within a few years.

A dam's safety relies on its ability to retain the reservoir under flood and earthquake loads. How will those loads change in response to global

warming? **We don't know**. We're like Alice trying to remember things before they happen.

Flood estimates will decrease as stream flow decreases but will increase during extreme events. How shall we estimate the design flood?

Novo-hydrology of extreme events will estimate new design floods. Our hydrologists will be challenged to make sense of the future.

Mantle will continue to shift in response weight re-distribution. Earthquakes are likely to change spatially and in magnitude. They are likely to occur where they haven't occurred historically. Currently active earthquake zones may become quiet. There is a school of thought that ties earthquake activity (M>7) to the slowing in the earth's speed of rotation approximately every 32 years. Causation has not been established.

Novo-tectonics of earthquakes will estimate new design earthquake loads. Our geologists and seismologists will be challenged to make sense of the future.

It's not unreasonable to suggest that volcanic activity will increase in frequency and location. New data from the Mariana back-arc where the Pacific tectonic plate subducts beneath the Philippine Sea plate detected an eruption not previously known. Krakatoa's recent eruption triggered a deadly tsunami. Closer to home, a mass of warm rock rising under New England was discovered in a study in the EarthScope program to reveal the processes that result in earthquakes and volcanic eruptions.

Yes . . . times they are a-changin'. Let's start swimmin'