Colorado River Tides[1]

A New Look at River Flow Through the Grand Canyon

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Introduction

Like many boatmen, on arrival at camp I place a rock or stick at water's edge to keep an eye on the river level. Often I've noticed that the times the Colorado River bottomed out or crested seemed at odds with the tide table I'd downloaded before the trip. I suspected that either typical flow varied a lot or that the commonly used tables were wrong.

While anticipating level changes is not mission critical for a Grand Canyon River trip, knowing tide behavior can help you find propitious times to run tricky rapids and avoid beaching on a pile of rocks during daily lows and weekend flows.

I figured I could find the answer. So with the opportunity afforded by forced isolation, I took a close look at the plentiful water-level data. This data has been recorded by the U.S. Geological Survey (USGS) every 15 minutes over many years at Lees Ferry (river mile 0), Phantom Ranch (mile 88), and Diamond Creek (mile 226). I downloaded all measurements between 2009 and 2020—that's 1.26 million records.

After considerable effort to wrangle all the data, I have now solved the riddle. While a lot of noise exists in the flow, this doesn't inhibit reasonably accurate low-tide predictions. High tide varies more, but predictions are still pretty good.

It turns out the available tide tables fail significantly in three respects:

1. At common flows on days there are tides, water typically begins to rise at Lees Ferry between 6:45 and 7:00 am—not around 10am which is commonly cited.[2]
2. The discharge wave flows, not at the generally accepted 4.0 to 4.5 miles per hour (mph), but at a much speedier 4.25 to 5.7 mph. Also the flow runs much faster *after* Phantom than *before*, and we can use this distinction to refine predictions for the entire river.
3. Existing tables specify the time of rising and ebbing tide based on river flow. But "tide" implies significantly changing levels in the Canyon—by typically 5,000 to 8,000 cubic feet per second (cfs) on any given day (Wright and Grams, 2010, page 5). In this context, does *flow* mean low flow, peak flow, average flow, or midway between low and peak? And these values all change as you progress downriver. In this new table, ***flow*** means "low flow for the day at Lees Ferry."

This example demonstrates just how wrong existing tables are:

> Imagine a day with flow that varies from a low of 9,000 to a high of 16,000 cfs—a common occurrence. By the time you arrive at Diamond Creek (mile 226), the standard go-to table is behind by about 16 hours. If the current continued another hundred miles, actual flow would lap the tide table by ***an entire day***!

While I find the speed of the wave an interesting factoid, the true value of this analysis for river runners is an accurate tide table, so I'll start with that. While I looked at all data over a period of 12 years (2009–2020) for this analysis, the information becomes very thin below 6,500 cfs and above 11,400 cfs, as flows outside this range are infrequent. So I included only days with low-flow tides at Lees Ferry between the above parameters.

Tide Table

Start with your best estimate for your trip of low flow at Lees Ferry and use that to select the pair of columns to employ below. You will likely reference just one pair of columns for your entire trip. Then use your river mile to estimate when the tide will start to rise and fall. At Lees Ferry, the tide starts to rise within one hour of the estimate 87% of the time. And 86% of the time, it starts to fall within an hour and a half of the prediction. Accuracy diminishes a bit as you travel downriver but is still fairly good. Keep in mind there is often no discharge wave from the dam on summer weekends. Tide estimates are based on "river mile"—second column. River feature locations are approximate.

Note that I used "start rise" and "start fall" rather than "trough" and "peak." This is because the flow tends to stay near its peak level for a few hours so the time of the actual peak is not very useful. The river stays near its trough for a shorter but significant time. "Start rise" and "start fall" are the times at which the flow begins a rapid change that will last for a few hours. Assume the river will be near its low point for a couple hours preceding "start rise" and will be near its highest level for many hours preceding "start fall."

Low Flow at Lees Ferry		7,000 cfs		8,000 cfs		9,000 cfs		10,000 cfs		11,000 cfs	
Feature - Approx.	**Mile**	**Start Rise**	**Start Fall**	**Start Rise**	**Start Fall**	**Start Rise**	**Start Fall**	**Start Rise**	**Start Fall**	**Start Rise**	**Start Fall**
Lees Ferry	**0**	6:45 am	10:15 pm	6:45 am	10:15 pm	6:45 am	10:00 pm	6:45 am	9:45 pm	6:45 am	9:30 pm
Badger	**10**	9:06 am	12:16 am	9:00 am	12:12 am	8:55 am	11:54 pm	8:50 am	11:36 pm	8:46 am	11:19 pm
House Rock	**20**	11:27 am	2:17 am	11:16 am	2:10 am	11:05 am	1:49 am	10:56 am	1:28 am	10:47 am	1:08 am
Silver Grotto	**30**	1:48 pm	4:18 am	1:31 pm	4:08 am	1:16 pm	3:44 am	1:01 pm	3:20 am	12:48 pm	2:57 am
	40	4:09 pm	6:19 am	3:47 pm	6:06 am	3:26 pm	5:39 am	3:07 pm	5:12 am	2:49 pm	4:46 am
Nankoweap	**50**	6:30 pm	8:21 am	6:02 pm	8:04 am	5:37 pm	7:34 am	5:13 pm	7:04 am	4:51 pm	6:35 am
Little Colorado	**60**	8:52 pm	10:22 am	8:18 pm	10:02 am	7:47 pm	9:29 am	7:18 pm	8:56 am	6:52 pm	8:24 am
	70	11:13 pm	12:23 pm	10:34 pm	12:00 pm	9:58 pm	11:23 am	9:24 pm	10:48 am	8:53 pm	10:13 am
Hance	**80**	1:34 am	2:24 pm	12:49 am	1:58 pm	12:08 am	1:18 pm	11:30 pm	12:40 pm	10:54 pm	12:02 pm
Phantom Ranch	**90**	3:55 am	4:25 pm	3:05 am	3:56 pm	2:18 am	3:13 pm	1:35 am	2:32 pm	12:55 am	1:51 pm
Crystal	**100**	5:50 am	6:16 pm	4:58 am	5:43 pm	4:09 am	4:58 pm	3:23 am	4:14 pm	2:41 am	3:31 pm
	110	7:46 am	8:06 pm	6:50 am	7:31 pm	5:59 am	6:43 pm	5:11 am	5:56 pm	4:26 am	5:11 pm
Elves Chasm	**120**	9:41 am	9:56 pm	8:43 am	9:18 pm	7:49 am	8:27 pm	6:58 am	7:39 pm	6:11 am	6:51 pm
Bedrock	**130**	11:37 am	11:46 pm	10:36 am	11:05 pm	9:39 am	10:12 pm	8:46 am	9:21 pm	7:56 am	8:31 pm
Deer Creek	**140**	1:32 pm	1:36 am	12:28 pm	12:53 am	11:29 am	11:57 pm	10:34 am	11:03 pm	9:42 am	10:11 pm
Upset	**150**	3:27 pm	3:26 am	2:21 pm	2:40 am	1:19 pm	1:42 am	12:21 pm	12:46 am	11:27 am	11:51 pm
Havasu	**160**	5:23 pm	5:16 am	4:14 pm	4:28 am	3:09 pm	3:27 am	2:09 pm	2:28 am	1:12 pm	1:31 am
	170	7:18 pm	7:06 am	6:06 pm	6:15 am	4:59 pm	5:11 am	3:56 pm	4:10 am	2:58 pm	3:11 am
Lava Falls	**180**	9:14 pm	8:56 am	7:59 pm	8:02 am	6:49 pm	6:56 am	5:44 pm	5:53 am	4:43 pm	4:51 am
	190	11:09 pm	10:46 am	9:52 pm	9:50 am	8:39 pm	8:41 am	7:32 pm	7:35 am	6:28 pm	6:31 am
	200	1:04 am	12:36 pm	11:44 pm	11:37 am	10:29 pm	10:26 am	9:19 pm	9:17 am	8:13 pm	8:11 am
Pumpkin Spring	**210**	3:00 am	2:27 pm	1:37 am	1:25 pm	12:20 am	12:11 pm	11:07 pm	11:00 am	9:59 pm	9:51 am
	220	4:55 am	4:17 pm	3:30 am	3:12 pm	2:10 am	1:55 pm	12:55 am	12:42 pm	11:44 pm	11:31 am
Diamond Creek	**230**	6:50 am	6:07 pm	5:22 am	4:59 pm	4:00 am	3:40 pm	2:42 am	2:24 pm	1:29 am	1:11 pm
	240	8:46 am	7:57 pm	7:15 am	6:47 pm	5:50 am	5:25 pm	4:30 am	4:07 pm	3:14 am	2:51 pm
	250	10:41 am	9:47 pm	9:08 am	8:34 pm	7:40 am	7:10 pm	6:17 am	5:49 pm	5:00 am	4:31 pm
	260	12:37 pm	11:37 pm	11:00 am	10:21 pm	9:30 am	8:55 pm	8:05 am	7:31 pm	6:45 am	6:11 pm
	270	2:32 pm	1:27 am	12:53 pm	12:09 am	11:20 am	10:39 pm	9:53 am	9:14 pm	8:30 am	7:51 pm
Pearce Ferry	**280**	4:27 pm	3:17 am	2:46 pm	1:56 am	1:10 pm	12:24 am	11:40 am	10:56 pm	10:15 am	9:31 pm

Speed (mph)	Wave	Peak	Wave	Peak	Wave	Peak	Wave	Peak	Wave	Peak
Lees -> Phantom	4.3	5.0	4.4	5.1	4.6	5.2	4.8	5.4	5.0	5.5
Phantom -> Diamond	5.2	5.5	5.3	5.6	5.5	5.7	5.6	5.9	5.7	6.0

For any pair of columns above the speed of the discharge wave (most relevant) is represented by the value on the left. The speed of peak flow is represented by the value on the right.

Approach to Tide Table Construction

I downloaded 1.26 million flow measurements from the National Water Information System operated by the USGS.[3] This download represents measurements taken every 15 minutes over 12 years (2009–2020) at three locations.[4]

1. Lees Ferry – mile 0
2. Phantom Ranch – mile 88
3. Diamond Creek – mile 226

I started by picking random days and graphing flows at each of these spots and I discovered that—while a great deal of noise exists—useful patterns emerge.

Precipitation and inflows from side streams and springs cause rises from station to station, but evaporation counterbalances some of this increase. In the absence of significant rain, an average of 490 cfs augments the flow between Lees Ferry and Phantom Ranch (Wright and Grams, 2010, page 4) and another 520 cfs is added between Phantom Ranch and Diamond Creek. It was gratifying (to me) to see that a torrential rain at Granite Park that hammered us one night in 2018 showed up as a significant spike at Diamond Creek about three hours after the storm.

My biggest challenge was identifying a signature event each day at Lees Ferry that I could spot later as it passed Phantom Ranch and Diamond Creek. My first inclination was to hone in on "peak flow," as it's relatively easy to construct a formula that flags a maximum in a data series over a given period of time. I had to account for long plateaus and for many occurrences of the data fluttering between two high values but this was tractable. Unfortunately, peak flow travels materially faster than lower flows and using peak flow inflates discharge wave speed. The peak also flattens as the discharge wave moves downriver, creating difficulties in estimating when the water level begins to drop.

I had to find a marker that accounted for the flow of the entire wave of water released by the dam each day. After many false starts, I settled on the "final minimum flow before a consistent rise." For example, here is the morning series at Lees Ferry on the 26th of April 2016—a typical Tuesday:

Time (am)	5:45	6:00	6:15	6:30	6:45	7:00	7:15	7:30	7:45
Flow (cfs)	8,800	8,800	8,800	8,800	8,900	9,000	9,100	9,300	9,500

Based on the above table, I used 6:30 am as the timestamp for Lees Ferry that I then compared with the same inflection points at Phantom Ranch and Diamond Creek. (Note that I rounded all values to the nearest hundred cfs).

Using markers constructed by this method at all of the three gauge stations, I was able to produce charts depicting the same discharge wave at the three locations. Here is the 24-hour chart for the flow originating at Lees Ferry on the 26th of April 2016 at 6:30 am:

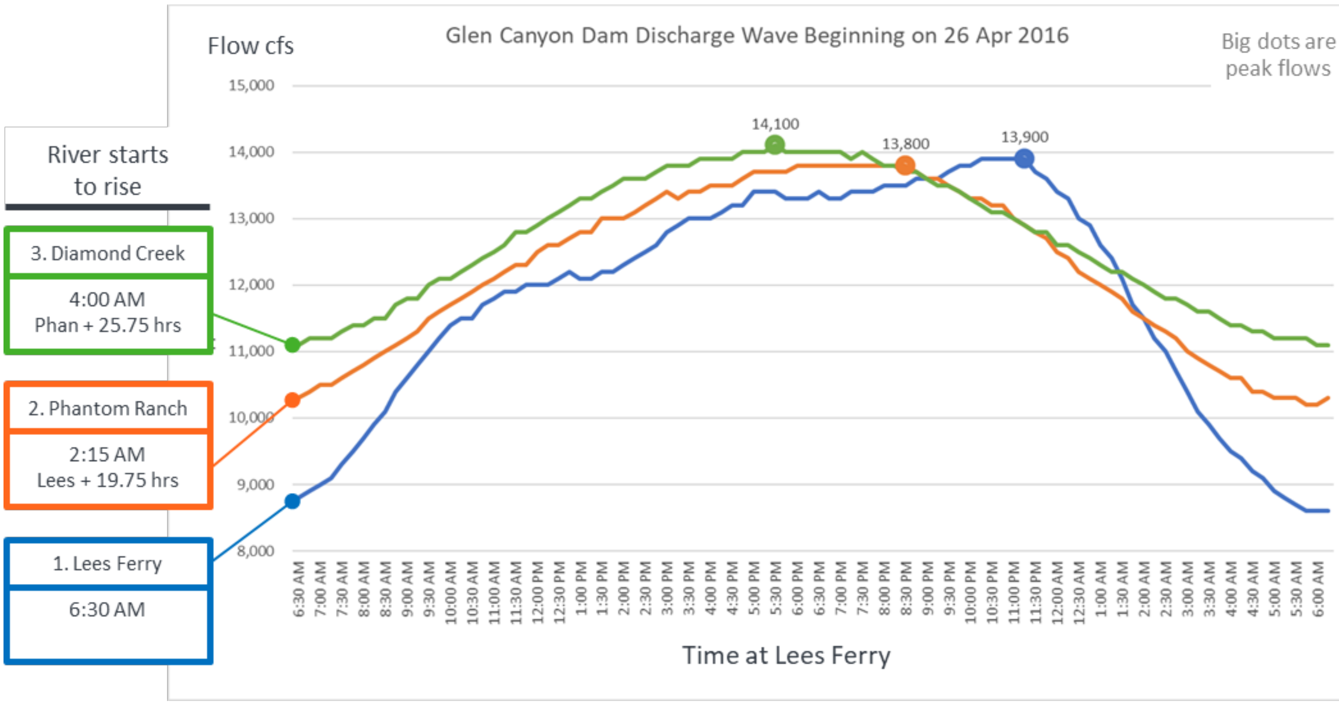


Chart 1

Note that on this day additional inflow from side streams and springs accounts for 420 cfs between Lees Ferry and Phantom Ranch, and 410 cfs between Phantom Ranch and Diamond Creek. You can see the discharge wave smooths progressively as it moves downriver. Examining more such charts revealed other useful patterns. The first chart I constructed took 45 minutes, and it was tedious work. With a little visual basic code, I built a dynamic model that produces a chart for any day between 2009 and 2020.

A user of the model can plug in any day between 2009 and 2020 to access a visualization of three overlapping waves as in Chart 1 above. I'm happy to share the model with anyone who is interested.[5]

Discharge Wave Evolution

On most days, the Glen Canyon Dam, 15.5 miles upriver from Lees Ferry[6], begins to increase its discharge in the early morning hours. The first sign of this rising flow passes Lees ferry between 6:45 and 7:00 am. The flow then may follow one of many variations on a common pattern represented in Chart 2 below.

If you imagine starting with low flow from the dam, then increasing for a number of hours, then stabilizing at a high level for a while before dropping back to low flow, you can picture a "discharge wave" informally referred to as a "bubble" starting at the dam and stretching about 120 miles downstream. Often there will be five successive waves emitted by the dam between Monday and Friday followed by about 240 miles of relatively constant low water representing "weekend flow." Here is what an idealized series of five waves might look like. Think of this as a snapshot of 7 days of flow at one moment in time as if water could flow freely 900 miles past Lees Ferry:

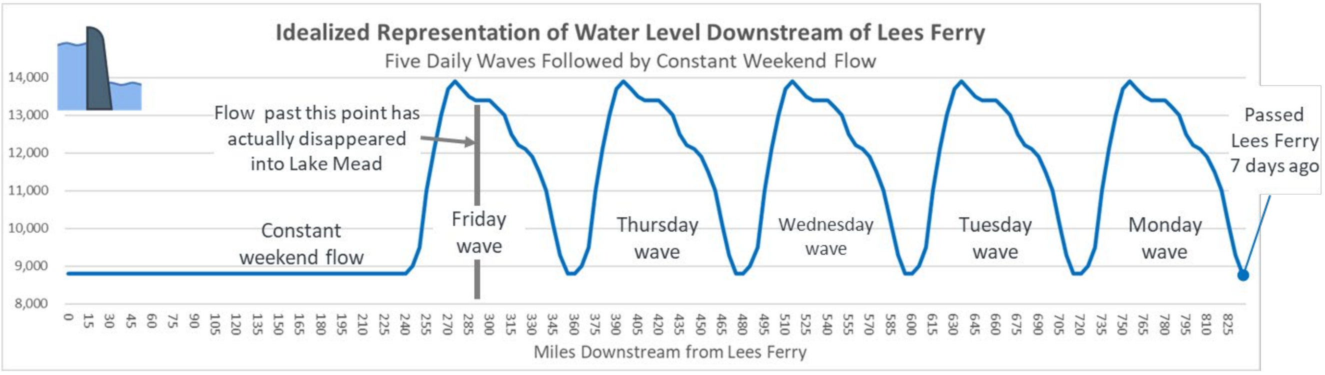


Chart 2

Chart 2 is one picture of flow for which there are many daily and weekly variations. (Note that the Tuesday wave in this depiction accurately represents the flow at Lees Ferry on Tuesday, 26 April 2016. It is the only accurate wave in this stylized representation. The days varied somewhat and there were tides on the weekend.)

If instead of taking a snapshot of all seven days of flow at once, you graph the changing flow at a single point such as Lees Ferry, you get exactly the same pattern—except reversed. The flow on the far right of Chart 2 above was the first part to pass Lees Ferry at about 7 am seven days ago and everything to the left of it followed. Chart 3 is a depiction of the water level at Lees Ferry over the same seven days. Note the x-axis now represents time of day instead of miles from Lees Ferry, and Chart 3 is a horizontally reversed version of Chart 2.

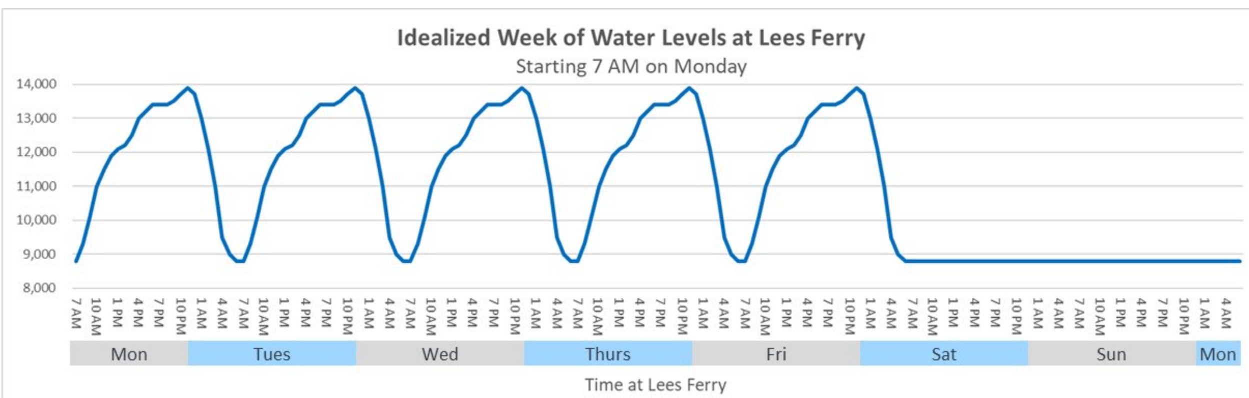


Chart 3

In other words, graphing the river level at Lees Ferry over a period of a day or more depicts a discharge wave with its leading face on the left and its tail on the right of the curve. You can still get a view of the shape of five successive waves if you picture the left side of Chart 3 as the leading edge and the right side (weekend flow) as trailing edge of the snapshot. It's important to understand this non-intuitive reversal to follow the rest of the description.

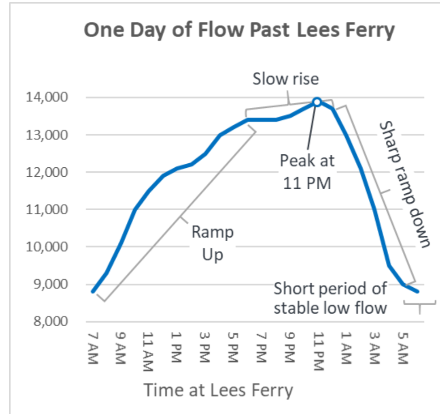


Chart 4

Chart 4 represents a typical day at Lees Ferry. Flow increases steadily until about 10 am and then continues a slow ramp up until early evening. Flow rises very slowly for a few hours, peaking at 11 pm, and then begins a sharp drop off before midnight, approaching low flow in the early morning hours. It stays low for 45 to 90 minutes and then begins to rise. This is a common pattern , but there are many variations on this theme.

In Charts 2 and 3 above, I simplified the multiday discharge waves a great deal. As waves move downriver, they evolve in predictable ways. Using the example wave we have been working with, let's take a look at various aspects of that evolution. Chart 5 shows three views of the wave that started at Lees Ferry at 6:30 am on the 26th of April 2016:

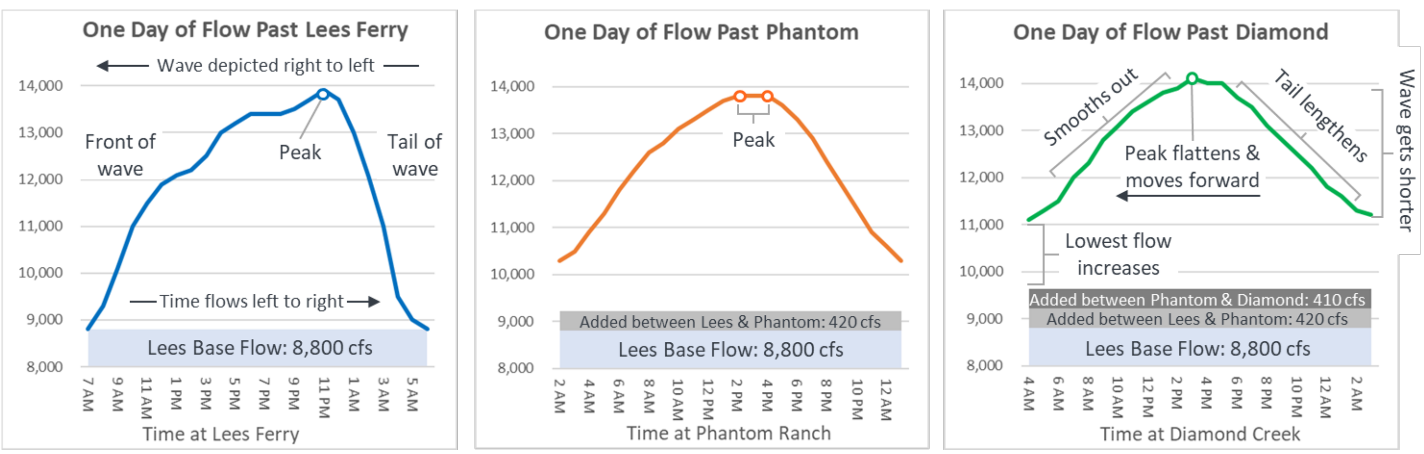


Chart 5

The most notable changes in the shape of any significant wave between Lees Ferry and Diamond Creek are:

- Jagged places smooth out.
- The base spreads and comingles with the preceding and following days' flows (Lazenby, 1987, page 1).
- The tail lengthens substantially.
- Peak flow moves faster than lower flow and progresses forward—to the left—on the wave (Lazenby, 1987, page 5).
- Often, the peak flattens as the wave moves downriver, increasing the uncertainty of the time the wave starts to fall.
- Variation between minimum and maximum flow decreases.

Charts 6 and 7 below reveal the details of the collapsing wave as minimum flow rises and the peak falls. The difference between high and low flows diminishes from 5,100 to 3,500 to 2,950 cfs. Note that the maximum flow at all three gauge stations remains pretty close to the same value because the shortening of wave height is counterbalanced by inflows and the rising of the lowest point of the wave due to flattening (as high points drop, low points rise).

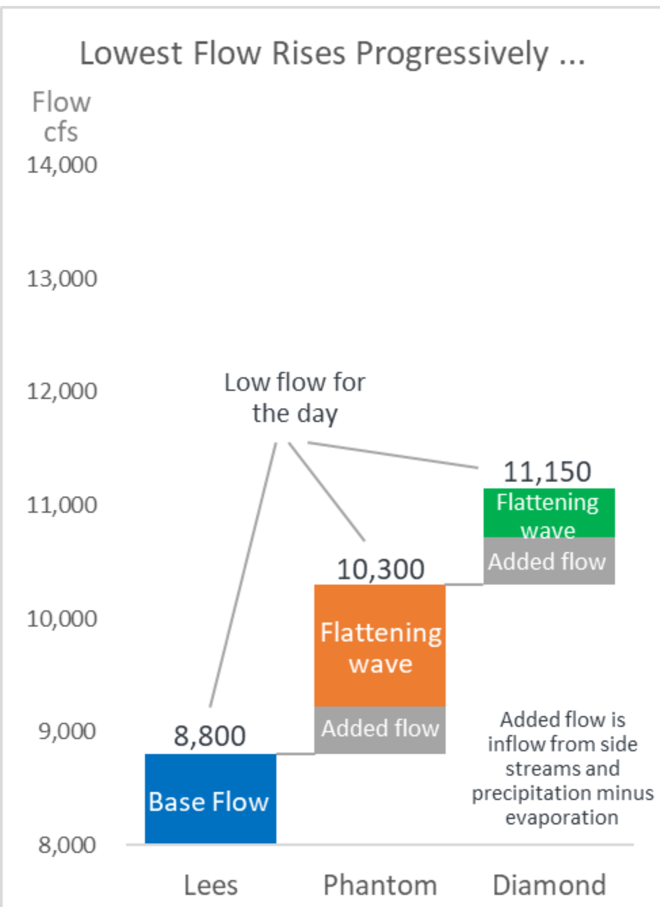


Chart 6

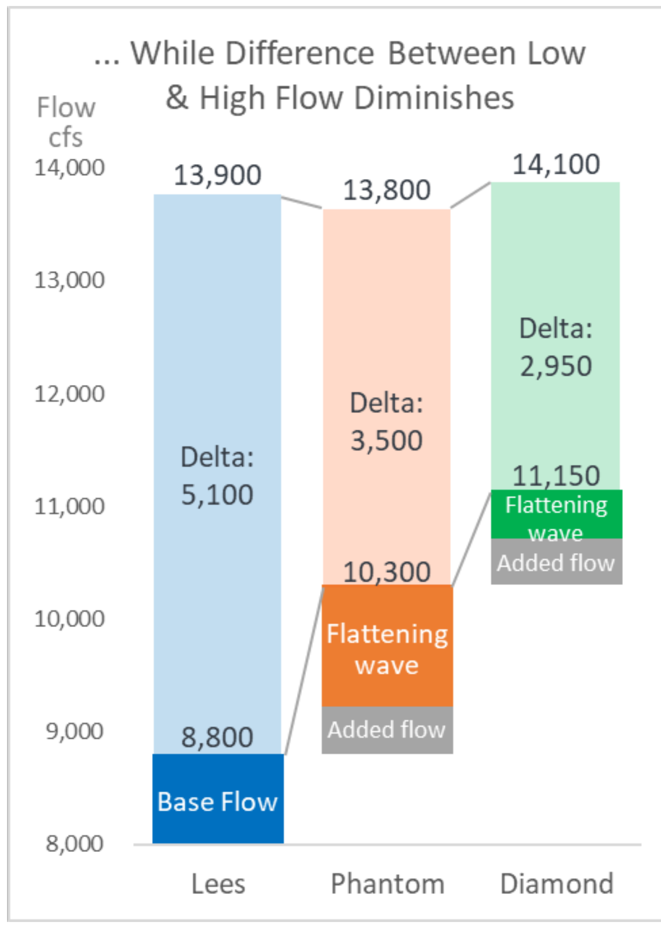


Chart 7

Start Time of Rising Tide at Lees Ferry

All of the varying estimates I have seen of the start of the rising tide at Lees Ferry are at odds with data logged at the Lees Ferry gauge station. On days with significant tides (at least 2,000 cfs difference between low and high tide), over 87% of the time the tide starts to rise within an hour of the common 6:45 to 7:00 am window.[7]

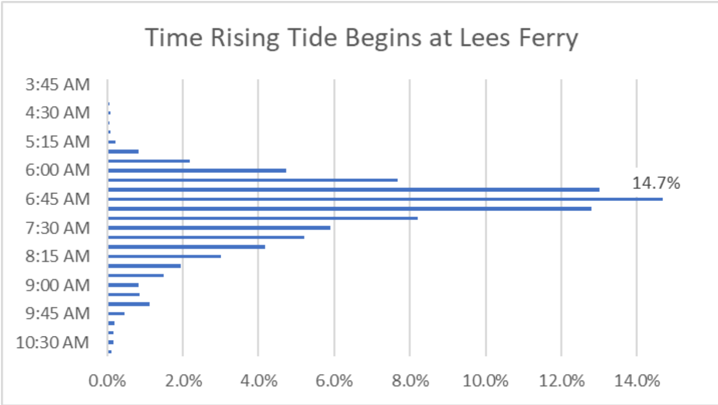


Chart 8

For years the Bureau of Reclamation has advised boatmen that the river at Lee's Ferry starts to come up about 10am (see sidebar below). While highly inaccurate, 10am is still a good rule of thumb for planning a launch because much of the prior drop off below the 10am level will have occurred in the early morning and by 10am flow is increasing rapidly. The problem is that 10am is a terrible baseline for projecting flow downstream leading to huge errors in estimating high and low tides and in wave speed.

Discharge Wave Speed

Note that "wave speed" is quite different than the speed of the water. The average downriver speed of the water molecules themselves is a leisurely 2.3 miles per hour when the river is running 15,000 cfs and 4 mph at a torrential 45,000 cfs.[8] The water molecules linger along the way as they swirl in eddies and engage with various obstructions (Graf, 1997, page 2). The discharge wave propagates through water at a much higher speed than the water itself just as sound speeds through the medium of relatively stationary air molecules.

Most sources I have come across claim the wave flows between 4.0 and 4.5 miles per hour. Some sources claim the wave flows as fast at 5.0 miles per hour at very high levels. In fact, at common levels, the wave travels between 4.15 and 5.85 miles per hour.

A Canyon Noir Mystery

On April 20, 2021 I spoke with a staff member at the Bureau of Reclamation that I'll call Flo. I asked Flo for help understanding why water so often starts to rise at Lees Ferry before 7am implying an implausibly early 4am ramping up at the dam. (It takes 3 hours for the discharge wave to travel from the dam to Lees ferry - Lazenby, 1987, page 8)

Flo explained that a 4am start makes sense because regulations limit how much the dam can increase its release per hour so if they start to ramp up about 4am they can be at high water by mid-morning.

In a bizarre twist, next morning Flo emailed to say that Lees Ferry actually comes up at 10am. When I confronted her with public data showing the water at Lees Ferry beginning to rise at 6:45am that very morning (link), Flo said the Bureau was formally retracting all previous comments.

Simple mistake or nefarious plot tied to the seamy underworld of western water politics? Jake Gittes is on the case.

Speed of Discharge Wave Above and Below Phantom Ranch

Few sources attempt to distinguish speeds above and below Phantom Ranch. Another interesting finding from my analysis is that the river flows about 0.85 mph faster below Phantom Ranch than it does above. We can use this distinction to improve the accuracy of tide tables for locations throughout the river corridor. Chart 9 summarizes these findings.

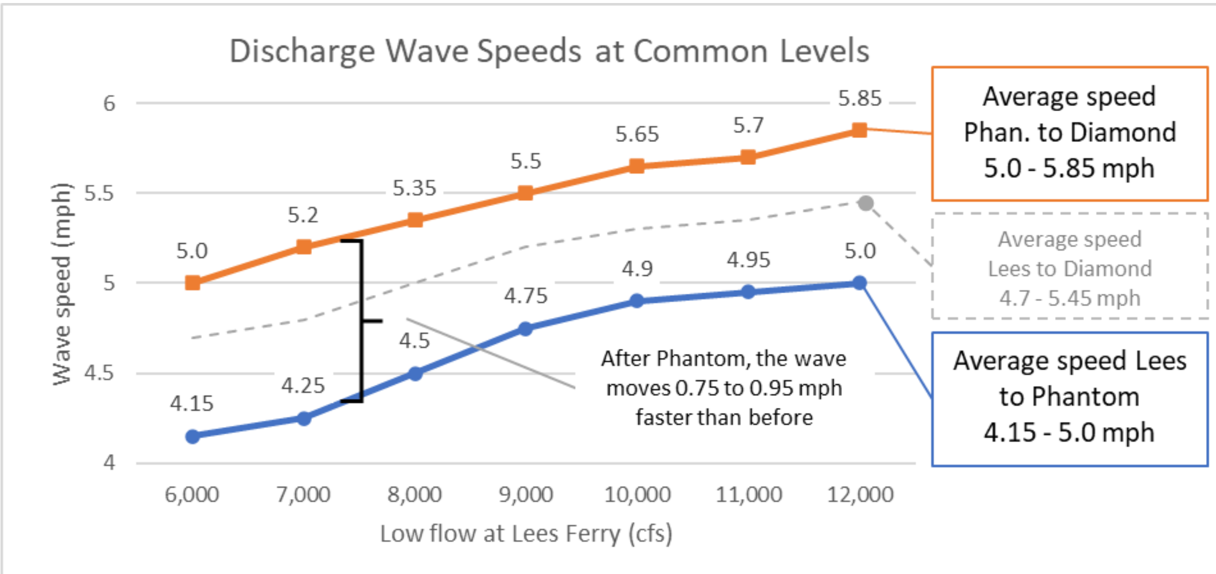


Chart 9

This chart ties out nicely with results of the only other study I could find of discharge wave speed. The 1987 paper – using data collected in 1985 – determined the speed from Lees to Phantom is 4.8 mph and phantom to diamond 5.3 mph (Lazenby, 1987, page 8). The paper did not distinguish between different water levels.

Speed of Peak at Common Levels

The timing of peak flow carries a fair bit of uncertainty. Indeed, the "peak" of a wave at Lees Ferry is often fairly flat, more akin to a mesa than a peak. And the wave tends to flatten as it progresses downriver, further complicating the assessment. A small variation in measurement could advance or delay the time the peak appears to pass a given point by 60 to 90 minutes—up to a three-hour window where a peak might appear in the data for a given wave.

While the discharge wave flows considerably faster than most sources claim, peak flow is faster still. In other words, the peak of the wave travels forward on the wave as it progresses downriver. This peak migration is another reason for higher uncertainty about the time the tide begins to ebb. Chart 10 shows the speed of peak flow before and after Phantom Ranch.

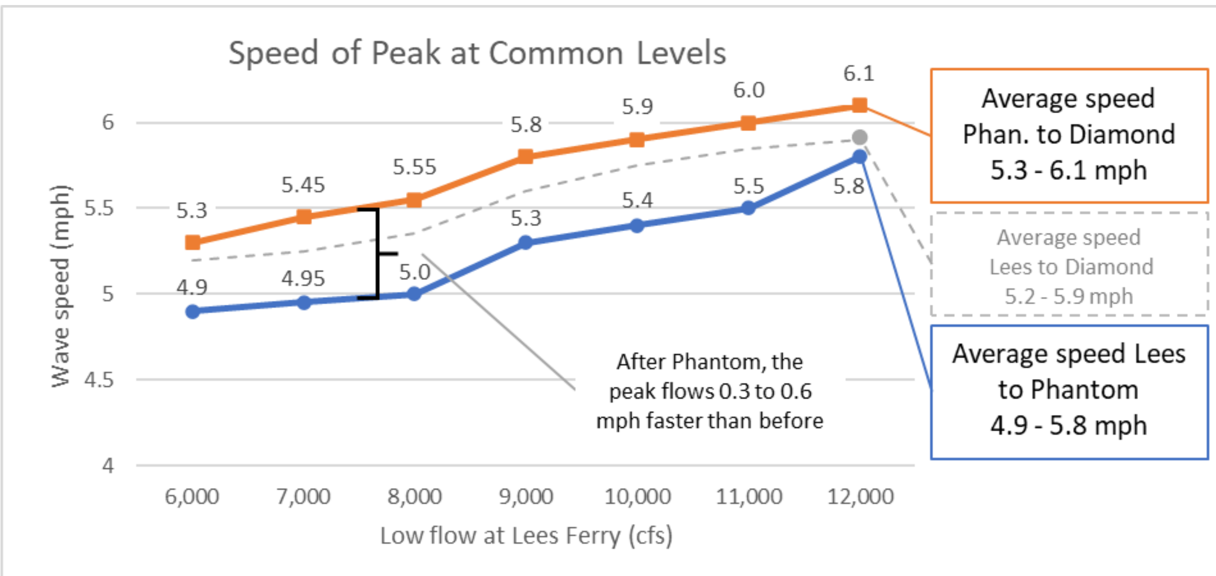


Chart 10

Faster Peak Flow Migrates Forward on the Discharge Wave

On average the peak flow moves 0.55 mph faster than the overall wave before Phantom Ranch and 0.25 mph faster after Phantom. When low flow at Lees Ferry is 9,000 cfs, peak flow on average travels:

- Ten miles more than the front of the wave by the time it reaches Phantom Ranch,
- An additional four miles more than the front of the wave by the time it reaches Diamond Creek.

It may seem counterintuitive that the peak accomplishes more than two-thirds of its movement in the first 88 miles of travel. Keep in mind that by the time the discharge wave reaches Phantom Ranch, the peak has used up much of its available runway atop the wave.

While the peak migrates toward the front of the wave, this movement may be counterbalanced by the wave lengthening. Lengthening, however, is usually inhibited by the front of today's wave running into the tail of yesterday's wave and the tail of today's wave colliding with the front of tomorrow's wave. As a result, each daily wave is about 24 hours in duration for the full length of the Canyon. It is about 102 miles long at the top of the river and 125 miles long in the faster water at the bottom.

Variations in Tides

About two thirds of the days during the sample period (2009 to 2020) adhered strongly to the common tide pattern at Lee's Ferry: begin rise in the early morning, continue to rise throughout the day and into the evening, then initiate a sharp drop before midnight.

Weekend Flow

In recent years, most Saturdays and Sundays from May through August have had "weekend flow." During this period there is no discharge wave on Saturday and Sunday and the river remains at low flow from early Saturday morning until Monday morning. U.S. national holidays – notably Memorial Day and Independence Day – also have weekend flow.

Between 2018 and 2020 the U.S. Department of the Interior experimented with what they called "bug flow." This was an attempt to better understand how to improve egg-laying conditions for aquatic insects. On spring and summer weekends during this period, rather than just running the dam at a constant low, the Bureau experimented with a variety of flows. Don't count on summer weekend low flows.

Winter Double-Peaks

About 8.5 percent of the days in the sample have double peaks. Double peaks typically occur between January and March.

Ramp up starts as usual at about 6:45am and continues until mid-morning when flow experiences a sharp drop off. This is followed by another rise starting in the early evening. The dip in the middle of the discharge wave smooths considerably or even disappears completely as the wave proceeds downriver (see chart 11).

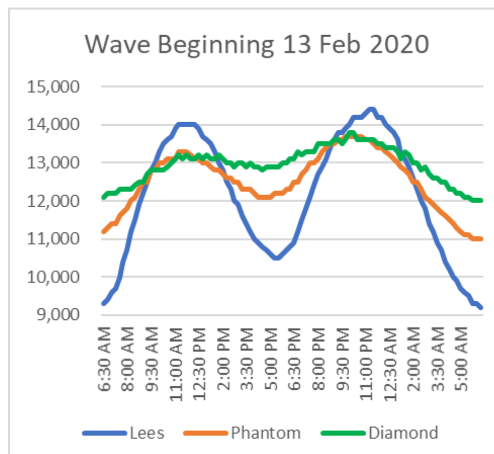


Chart 11

2011 High Water Testing

Between late February and December 2011, the USGS conducted flow testing in hopes of finding a way to stem erosion of Grand Canyon beaches (Wright and Grams, 2010). For most of this period the river ran at constant daily flows between 15,000 and 25,000 cfs.

Other Experimental Flows

The U.S. Department of the Interior periodically runs experimental flows. Be sure to find out before you launch if you should expect any significant deviations from typical flows during your trip. Most recently, in November 2018, the dam increased from a daily flow between 6,000 and 9,000 cfs to a sustained flow of 38,100 for three days (National Park Service, 2018). The increase from low to high was about 4,000 cfs per hour over about 8 hours. You definitely want to avoid being surprised by a spike like this.

Conclusion

I hope that, armed with an improved tide table, boatmen will be better able to understand river flow, avoid surprise overnight beaching of their flotilla and better time their running of challenging rapids. I wish you good floating and hope to see you on the river in the future.

Endnotes

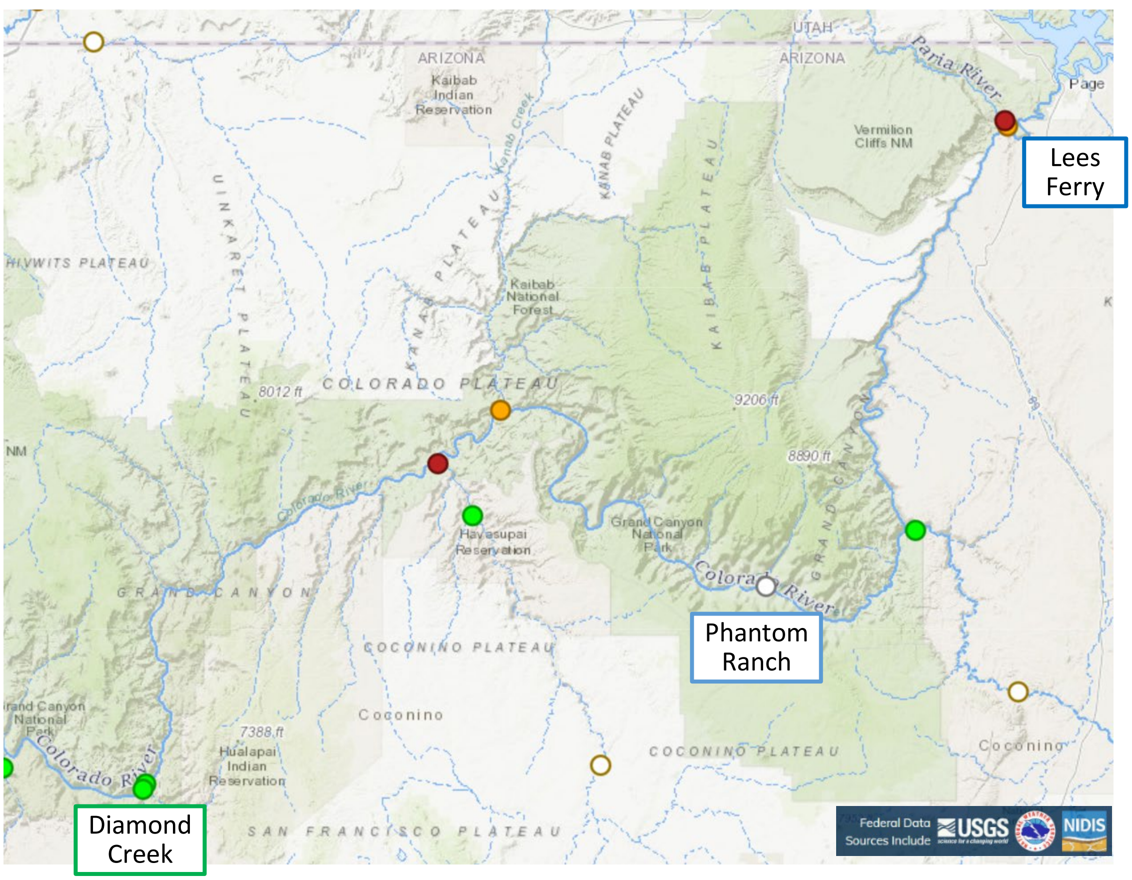
1. Of course, rivers don't actually have tides. The word *tide* is a useful and concise shorthand to describe the daily rising and falling of river flow caused by varying levels of the discharge wave.

2. A 1985 study found that the discharge wave from the dam takes about 3 hours to reach Lees Ferry (Lazenby, 1987, page 8), so a 6:45am ramp-up time at Lees Ferry implies the Glen Canyon Dam starts to ramp up flow around 3:45am.

   Most of Arizona does not observe daylight savings time and is on Mountain Standard Time (MST) all year. So Arizona is on Pacific Time between mid-March and early November, and on Mountain Time the rest of the year.

3. Data is available from the National Water Information System operated by the U.S. Geological Survey for three locations in the Grand Canyon:

   Lees Ferry: https://waterdata.usgs.gov/usa/nwis/uv?09380000. Flow data since 1985
   Phantom Ranch: https://waterdata.usgs.gov/az/nwis/uv?09402500. Flow data since 1980
   Diamond Creek: https://waterdata.usgs.gov/nwis/uv?09404200. Flow data since 1983

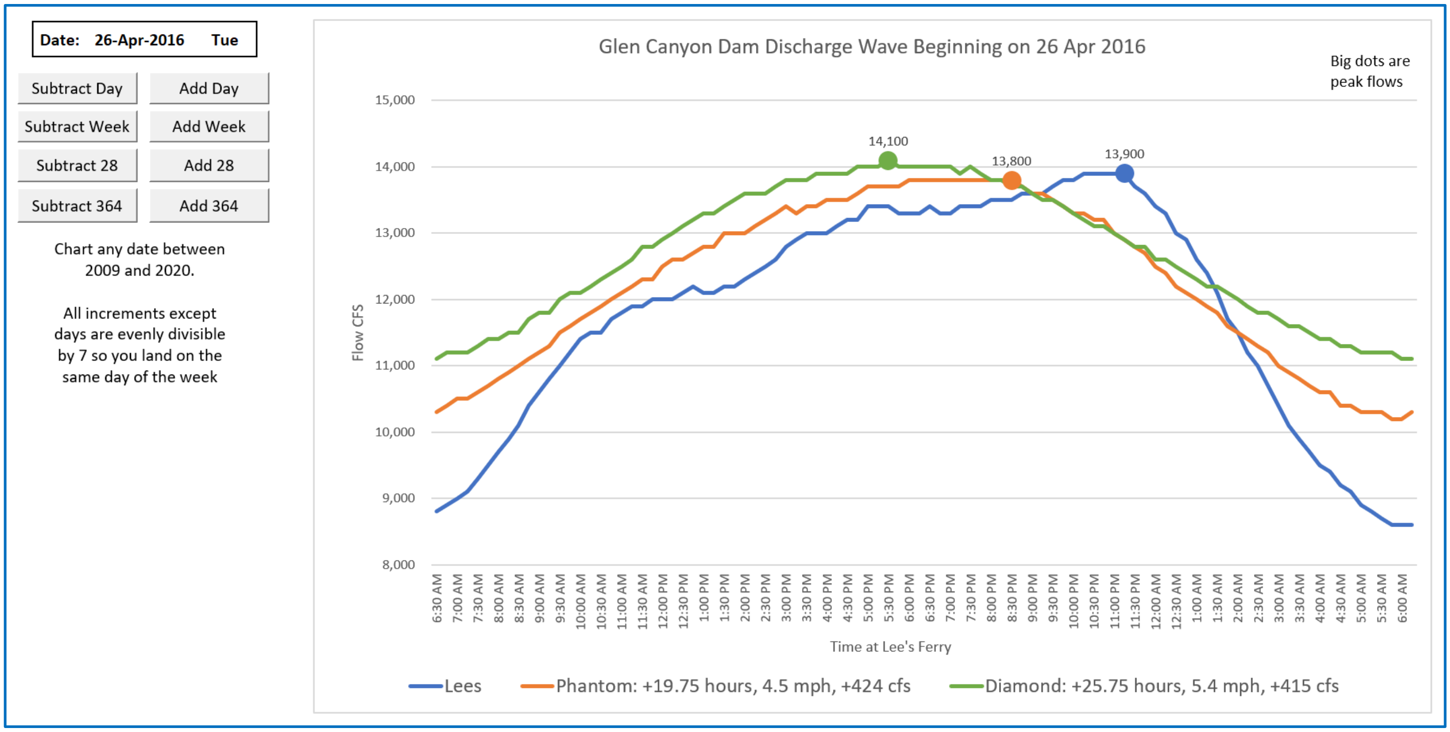


This very cool USGS interactive map can be accessed here.

4. Of the expected 420,769 records for each location, a few were missing:
   - Lees Ferry: 41 missing records
   - Phantom Ranch: 31 missing records
   - Diamond Creek: 15 missing records

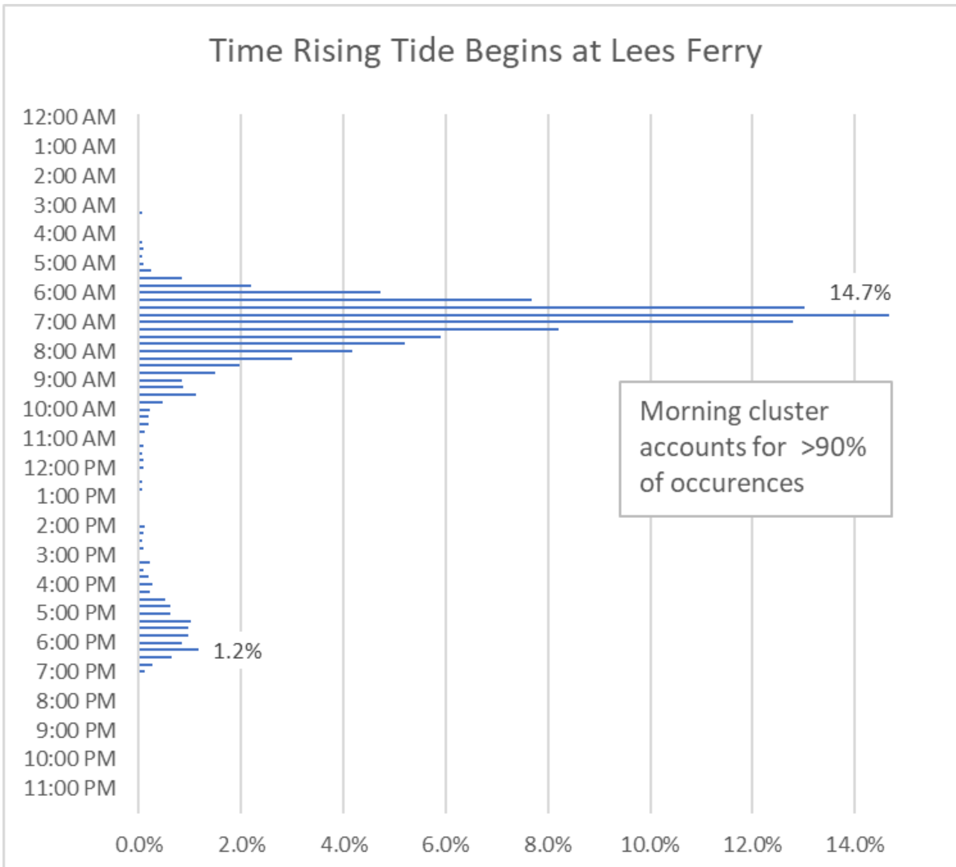
   Oddly, 16 of these 87 misses occurred on one day, 20 April 2009—Weed Day. Weird. I filled the gaps with dummy data. This addition did not distort the results at all.

5. The model is a 120 MB Excel file. It includes macros so security warnings will display on opening. You'll need a recent version of Excel and a laptop or desktop computer with a good processor to run it. The model contains a number of tools including a visualization of three views of a single discharge wave for any day between 2009 and 2020—example below. If you would like a copy, email p@HairyBoatman.com.



6. There is a surprising amount of disagreement about how far Lees Ferry is below Glen Canyon Dam. Wright and Grams state the distance is 15.5 miles (page 2). Kurt Schonauer of the US Geological Survey confirmed the distance is about 16 miles. A 1985 study found the discharge wave takes about three hours to travel from the dam to Lees Ferry (Lazenby, 1987, page 8).

7. Here is a 24-hour picture of the time rising tide begins. The late afternoon/evening cluster most commonly occurs on days between January and March as the first step of a second wave for the day. This second cluster was omitted from analysis to focus attention on the much more common morning cluster:



8. During special flows in 1991 and 1996, the U.S. Geological Survey released florescent dye at the dam and at Lees Ferry and used it to determine river speed—i.e. speed of the water molecules, not the wave—to various locations.

Selected References

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Lazenby, Jerold F. “Unsteady Flow Modeling of the Releases from Glen Canyon Dam at Selected Locations in the Grand Canyon” (1987). *Elusive Documents.* Paper 24. Link

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Schonauer, Kurt (Hydrologist, USGS Arizona Water Science Center, Flagstaff, AZ). April 2021. E-mail.

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Wiele, S. M., and Smith, J. D. “A Reach-Averaged Model of Diurnal Discharge Wave Propagation Down the Colorado River Through the Grand Canyon.” *Water Resources Research*, (32)5, pages 1375–1386, 1 May 1996. Abstract Link. A significant fee may be assessed to access this document.

Wright, S.A., and Grams, P.E. “Evaluation of Water Year 2011 Glen Canyon Dam Flow Release Scenarios on Downstream Sand Storage Along the Colorado River in Arizona.” U.S. Geological Survey Open-File Report 2010-1133. 2010. Link