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Fill Mead First: A technical assessment

John C. Schmidt, Department of Watershed Sciences, Utah State University, Logan UT
with contributions from Maggi Kraft, Daphnee Tuzlak, and Alex Walker

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This publication is the first in a series of white papers from the Future of the Colorado River Project. Also included in the series:

White Paper 2. Water Resource Modeling of the Colorado River: Present and Future Strategies

The CRSS is an important water-policy planning tool that has been used by the Bureau of Reclamation and other stakeholders in numerous major efforts such as negotiation of the 2007 Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, the 2012 Colorado River Basin Water Supply and Demand Study, and the 2015 Glen Canyon Dam Long-Term Experimental and Management Plan. Given the complexity of the CRSS, experts and stakeholders must invest significant resources to explore alternative paradigms to manage water supply in the Colorado River system, such as alternative strategies that might enhance water supply reliability and/or river ecosystem health. This white paper explores alternative management strategies for the Colorado River that might provide benefit to water-supply users and to river ecosystems.

White Paper 3. Managing the Colorado River for an Uncertain Future

Colorado River managers face many uncertainties—issues like climate change, future water demand, and evolving ecological priorities—and are looking for new tools to help cope with this uncertain future. They need new ways to help classify uncertain conditions, manage for uncertain conditions, and to create models in the face of a slew of oncoming unknowns. To help Colorado River stakeholders think about, talk about, and better manage the future river, the Center for Colorado River Studies offers a new white paper that distinguishes four levels of decision-making uncertainty and suggest tools and resources to manage the different levels.

For more information:

John C. Schmidt, Director
Center for Colorado River Studies
jack.schmidt@usu.edu
qcnr.usu.edu/coloradoriver

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Maggi Kraft and ***Alex Walker*** are graduate students in the Department of Watershed Sciences, USU. ***Daphnee Tuzlak*** is a graduate student in the Department of Geology, USU.

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Executive Summary

The Fill Mead First (FMF) plan would establish Lake Mead reservoir as the primary water storage facility of the main-stem Colorado River and would relegate Lake Powell reservoir to a secondary water storage facility to be used only when Lake Mead is full. The objectives of the FMF plan are to re-expose some of Glen Canyon's sandstone walls that are now inundated, begin the process of re-creating a riverine ecosystem in Glen Canyon, restore a more natural stream-flow, temperature, and sediment-supply regime of the Colorado River in the Grand Canyon ecosystem, and reduce system-wide water losses caused by evaporation and movement of reservoir water into ground-water storage. The FMF plan would be implemented in three phases. Phase I would involve lowering Lake Powell to the minimum elevation at which hydroelectricity can still be produced (called minimum power pool elevation): 3490 ft asl (feet above sea level). At this elevation, the water surface area of Lake Powell is approximately 77 mi^2, which is 31% of the surface area when the reservoir is full. Phase II of the FMF plan would involve lowering Lake Powell to dead pool elevation (3370 ft asl), abandoning hydroelectricity generation, and releasing water only through the river outlets. The water surface area of Lake Powell at dead pool is approximately 32 mi^2 and is 13% of the reservoir surface area when it is full. Implementation of Phase III would necessitate drilling new diversion tunnels around Glen Canyon Dam in order to eliminate all water storage at Lake Powell. In this paper, we summarize the FMF plan and identify critical details about the plan's implementation that are presently unknown. We estimate changes in evaporation losses and ground-water storage that would occur if the FMF plan was implemented, based on review of existing data and published reports. We also discuss significant river-ecosystem issues that would arise if the plan was implemented.

Implementation of Phase I of FMF would allow the flow regime of the Colorado River in Grand Canyon to be more natural, but only if hydropower generation does not follow daily and weekly demands. Implementation of Phase II of FMF would unavoidably create a less natural flow regime. The primary limitation to re-establishing a natural flow regime is the capacity of the facilities that release reservoir water downstream to the Grand Canyon ecosystem. The capacity of the penstocks that route water to the power plant have a capacity of ~31,500 ft^3/s (cubic feet per second), and an additional ~15,000 ft^3/s can be released through the river outlets when the reservoir is at minimum power pool. However, the penstocks cannot be used when the reservoir is below minimum power pool, and the capacity of the river outlets decreases as reservoir elevation drops; the capacity of the river outlets is less than 5000 ft^3/s when the reservoir is near dead pool elevation. Thus, the largest releases from Lake Powell could only be ~45,000 ft^3/s during Phase I, even though typical incoming floods to Lake Powell exceed 50,000 ft^3/s in most years. If Phase II was implemented and

an attempt was made to maintain the reservoir at dead pool, releases downstream could be only 5000 ft^3/s. Whenever incoming floods to Lake Powell exceeded this flow rate, the temporarily drained reservoir would partially refill, especially during each year's spring snowmelt season. In wet years, reservoir elevation would rise more than 100 ft to minimum power pool elevation, and floods of 45,000 ft^3/s could occur, but only for as long as the reservoir remained above 3490 ft asl. ***A natural flow regime is likely to exist most of the time if Phase III of FMF was implemented.***

A renewable supply of fine sediment is necessary to maintain Grand Canyon's eddy sandbars that are used by river runners, create the architecture of aquatic habitat, and serve as a source of fine sediment to be redistributed by winds upslope to help protect archaeological sites. However, Phase I or Phase II would not change the existing condition of fine-sediment deficit that exists in Grand Canyon today, because ***water released from a partially drained Lake Powell in Phase I or Phase II would be devoid of fine sediment.*** Sediment eroded from the existing deltas in the Colorado River and San Juan River arms of Lake Powell would be re-deposited within the smaller Lake Powell, creating new, lower-elevation deltas in Glen Canyon. In Phase III, fine-sediment delivery into the Grand Canyon would probably be very large and would cause significant ecosystem adjustments associated with the sudden change from relatively clear water to a very turbid river. ***Impacts to the aquatic and riparian ecosystem, including to the existing population of endangered humpback chub, are potentially significant and would have to be monitored and managed adaptively***.

We estimate that there would be a small net decrease in total reservoir evaporation if Phase I or Phase II were implemented in comparison to present conditions. Implementation of FMF would decrease the combined surface area of the water stored in both reservoirs, and the evaporation rate from Lake Mead is not much more than from Lake Powell. However, the magnitude of the savings is less than the natural range in variability in evaporation. The rate of evaporation loss from Lake Mead has been measured by the U. S. Geological Survey (USGS) in a state-of-the-science program since 2010 (Moreo, 2013, 2015), and these measurements show that the annual evaporation loss rate is ~6.0 ft/yr and has varied between 5.5 and 6.4 ft/yr. There are no recent state-of-the-science measurements at Lake Powell; the average evaporation rate between 1965 and 1979 was 5.7 ft/yr and varied between 4.9 and 6.5 ft/yr. ***For purposes of public policy discussion, we conclude that there would be no change in evaporation losses if FMF was implemented.*** Movement of reservoir water into the ground-water system that surrounds Lake Powell is inevitable. Most of the ground water that has already moved into storage would return to the Colorado River during a period of decades to centuries after FMF was implemented. A small proportion of the reservoir water that has moved into the surrounding bedrock has been a true loss from Lake Powell, but this water has seeped around Glen Canyon Dam and returned to the Colorado River immediately downstream from the dam. Only a small proportion of ground-water storage immediately moves out of the surrounding bedrock when the reservoir is drawn down. Extrapolation of the results of Thomas' (1986) study concerning ground-water movement and storage north and west from Glen Canyon Dam and Wahweap Marina yields an estimate that between 2.1 and 9.0 million af moved into the bedrock surrounding Lake Powell between 1963 and 1983. Myers (2013a) estimated that ~12 million af moved into ground-water storage during that same period. Thomas' (1986) study was based on analysis of data from wells and a numerical model that was state-of-the-science at the time the study was published, but this model has coarse resolution by today's standards. Although there is large uncertainty in extrapolating Thomas' (1986) results to estimate of the total amount of reservoir water that moved into ground-water storage in the entire Lake Powell region, it is unlikely that this water has irreversibly moved elsewhere in the region. Myers' (2013a) study was based on a water-budget approach that also has large uncertainty. There is also very large uncertainty in estimating how long into the future reservoir water will continue to move into the surrounding bedrock. Thomas (1986) estimated that some movement of reservoir water into the

surrounding bedrock would occur for a period of between 80 and 700 years, assuming that the reservoir stays full most of the time. ***Based on the best estimates of Thomas (1986), the long-term future rate of movement of ground water into the surrounding bedrock is likely to be less than ~0.05 million af/yr (~50,000 af/yr), and would d***ecline to less ~0.03 million af/yr (~30,000 af/yr) after mid-21st century.

Assuming that movement of reservoir water into ground-water storage surrounding Lake Mead is small – an estimate suggested by water balance calculations but not yet verified by independent measurements of ground-water flow at wells – ***the projected water savings by implementing FMF would be less than ~0.05 million af/yr (~50,000 af/yr)***. It is a matter of public policy debate whether or not this magnitude of savings is sufficiently large to justify immediate reconsideration of many administrative and legal agreements concern-ing storage of water in Lake Powell and Lake Mead. At some time in the future, however, this magnitude of water savings might be viewed as sufficiently large to be worth serious engineering and scientific analysis and policy discussion. ***Now is the time to initiate new measurement programs of losses at Lake Powell and Lake Mead so that future policy discussions have access to less uncertain data regarding evaporation and ground-water storage.*** Initiation of a new measurement program of evaporation at Lake Powell, continuation of the present evaporation measurement program at Lake Mead, and initiation of a new phase of ground-water monitoring and modeling at Lake Powell and perhaps at Lake Mead would inform these discussions.

Establishment of new observation wells further and to the south from Lake Powell, coupled by development of modern, state-of-the-science numerical models of ground-water flow, would allow more precise estimates of future movement of reservoir water into the surrounding ground-water system. Establishment of a new gaging station to reduce uncertainty in estimating the amount of unmeasured inflow to Lake Powell would allow a more accurate water budget to be developed. In addition, implementation of FMF would have to be preceded by predictive modeling of fine-sediment redistribution within a partially drained Lake Powell so that reservoir releases would not further degrade the Grand Canyon ecosystem. Collectively, these data, analyses, and modeling tools would empower future water resource decision-makers to make informed decisions about management of Lake Powell and Lake Mead.

1. Introduction

The challenge of managing the Colorado River not only concerns how to sustainably meet increasing societal demands for water and electricity but also concerns how to rehabilitate the native ecosystems of those river segments that remain undammed. Although the undammed river segments play a significant role in water-supply conveyance and their flow regimes have been significantly perturbed by the existence and operations of dams and reservoirs, many segments still retain natural values of national significance.

The multiple objectives of providing secure water supplies by reservoir storage, generating renewable energy by producing electricity at power plants, and rehabilitating and/or recovering native ecosystems and endangered species dramatically compete where the Colorado River crosses the southern Colorado Plateau (Fig. 1). Nearly half of the 500 mi (miles) between the confluence of the Green and upper Colorado Rivers and the Grand Wash Cliffs have been impounded to create Lake Mead and Lake Powell reservoirs, the two largest in the United States. The flow regime and sediment supply of the 255 mi of the Colorado River between Glen Canyon Dam and Lake Mead is primarily controlled by the existence and operation of the dam, but this segment is also among the United States' most valued river ecosystems. Thus, the federal government, state governments, and many non-government organizations (NGOs) have considered alternative strategies to maximize the utilitarian uses of the Colorado River while also rehabilitating the ecological values of this part of the Colorado River.

The purpose of this paper is to provide a preliminary technical analysis of the Fill Mead First (FMF) proposal, which is an alternative to the present administrative rule of storing approximately equal volumes of water in Lake Mead

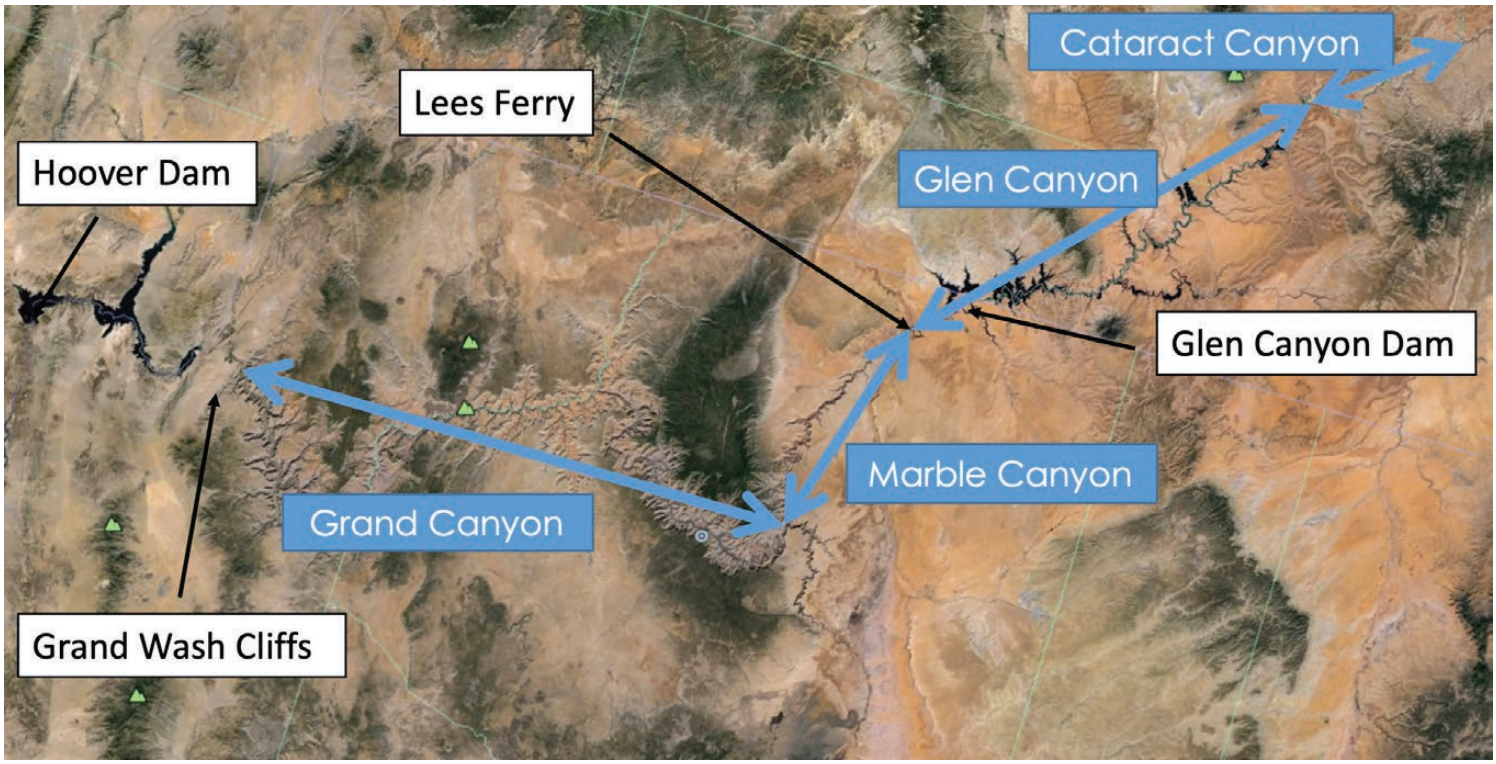


Figure 1. Map showing the Colorado River in the southern Colorado Plateau. Here, the Colorado River flows through Cataract Canyon, Glen Canyon, Marble Canyon, and Grand Canyon (blue lines), and exits the Colorado Plateau at the Grand Wash Cliffs. Most of Glen Canyon is inundated by Lake Powell that is created by Glen Canyon Dam; Lake Powell also inundates the downstream part of Cataract Canyon. The downstream 40 mi of Grand Canyon are inundated by Lake Mead; Hoover Dam, which forms Lake Mead, is 70 mi downstream from the Grand Wash Cliffs. Image from <https://www.google.com/maps/>.

and Lake Powell (hereafter called *the equalization rule*). The equalization rule was defined in the Long-Range Operating Criteria[1] adopted in June 1970. The Long-Range Operating Criteria was clarified and revised by the Interim Guidelines for the Operation of Lake Powell and Lake Mead[2] in 2007. In 2009, the Glen Canyon Institute (GCI), whose mission is "the restoration of Glen Canyon and a free flowing Colorado River," proposed the FMF plan wherein Lake Mead would be designated as the primary water storage reservoir of the Colorado River, and Lake Powell's role would be relegated to store water only when Lake Mead is full. The plan was clarified by Kellett (2013)[3] who described in conceptual terms a three-phase implementation strategy. The FMF plan has gained attention in the media and in popular literature (Beard, 2015[4]; Lustgarten, 2015[5], 2016[6]).

In this paper, we summarize the three phases of the FMF plan, and we identify critical details about the plan's implementation that are presently unknown. We argue that the magnitude of the water savings that might arise from implementation of FMF is probably small, but there is significant uncertainty in estimating the magnitude of these savings. We also identify significant river-ecosystem issues that would arise if the plan was implemented. Our goal is to encourage discussion about alternative strategies for storing Colorado River water that can meet society's water supply needs while also allowing rehabilitation of segments of the Colorado River.

2. Background

For purposes of this paper, we define the Grand Canyon ecosystem of the Colorado River as the segment between Glen Canyon Dam and the upstream end of Lake Mead. The most upstream 15 mi of the Grand Canyon ecosystem are the only part of Glen Canyon that remains undammed, and this part of the river is managed by the National Park Service as Glen Canyon National Recreation Area. The subsequent 60 mi between Lees Ferry and the confluence with the Little Colorado River are in Marble Canyon; further downstream, the Colorado River flows for 180 mi through the Grand Canyon to the point where Lake Mead is encountered near RM (River Mile) 240[7]. The river corridor in Marble and Grand Canyons is managed by Grand Canyon National Park, although the left bank of the river downstream from RM 164 is within the Hualapai Indian Reservation. Approximately 40 mi of the Colorado River in Grand Canyon between RM 240 and 280 are inundated by Lake Mead; Hoover Dam is located approximately 70 mi further downstream beyond the end of the Grand Canyon. Lake Powell inundates approximately 155 mi of Glen Canyon to Hite, as well as approximately 30 mi of the Colorado River upstream from Hite. The inundated area upstream from Hite is part of Cataract Canyon and includes Narrow Canyon.

The natural stream-flow regime and sediment supply of the Colorado River in the Grand Canyon ecosystem have been completely changed by the existence and operation of Glen Canyon Dam (Gloss et al., 2005)[8]. The large volume of Lake Powell is sufficient to completely store more than ~2 years of average runoff of the Colorado River, and the reservoir completely traps all of the fine sediment[9] that once flowed through Glen Canyon and into Marble Canyon. Operations of Glen Canyon Dam control how reservoir water is released downstream and therefore determine the stream-flow regime of the Colorado River in the Grand Canyon ecosystem. Little unregulated stream flow is delivered by the Paria or Little Colorado Rivers. The magnitude of annual floods has been reduced by nearly 60%, and the magnitude of base flows has been increased (Topping et al., 2003)[10].

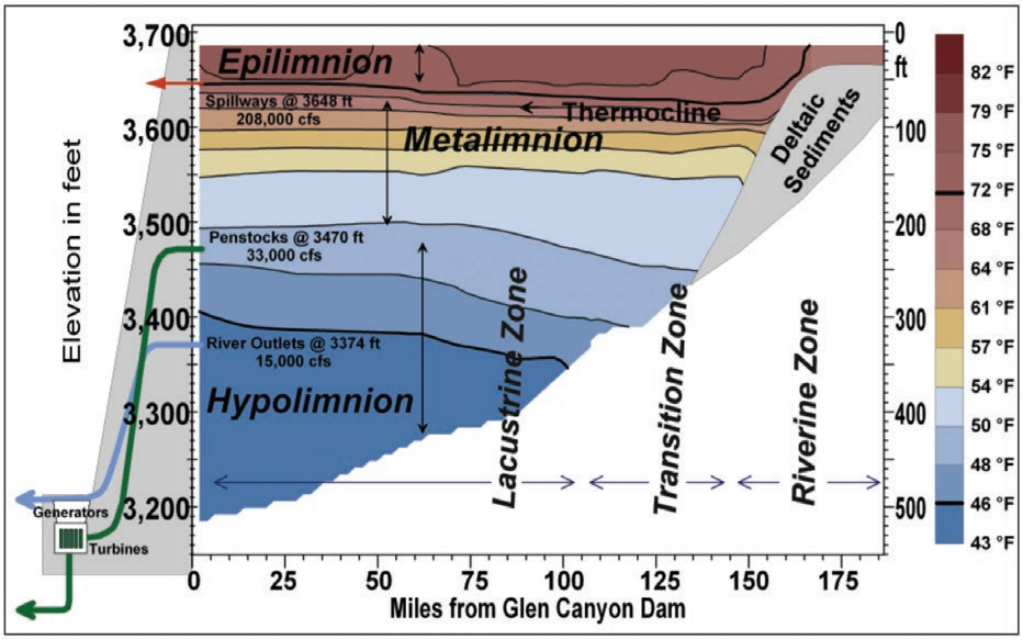


Figure 2. Diagram showing typical temperature stratification of Lake Powell at times when the reservoir is nearly full and showing the elevations of the three facilities through which water is released from Lake Powell to the downstream Colorado River. Also shown is the approximate location of the fine sediments that have accumulated in the Colorado River arm of the reservoir as a delta (Vernieu et al., 2005, figure 1)[61].

2.1. Glen Canyon Dam and Lake Powell

Glen Canyon Dam was constructed between 1956 and 1966, and storage of water behind the dam began in March 1963. The maximum height of Glen Canyon Dam is 710 ft (feet), of which 583 ft is above the lowest point of the former channel of the Colorado River. The crest of the dam is at 3715 ft asl (feet above sea level). The maximum normal water surface elevation of Lake Powell is 3700 ft asl. The maximum water surface elevation of Lake Powell that is predicted to occur if the Maximum Probable Flood entered the reservoir when it was already full is 3711 ft asl (Reclamation, 1989, 2010)[11],[12]. Water is released from Lake Powell through the spillways, the river outlets, and the penstocks that route water to the turbines in the Glen Canyon power plant (Fig. 2). The maximum capacity of the spillways is rated to be 208,000 ft^3/s (cubic feet per second) (Bureau of Reclamation data)[13]. Except for short-duration engineering tests in 1980 and 1984, the spillways have only been used in June 1983 when approximately 50,000 ft^3/s of reservoir water was released through these tunnels. There was substantial damage to the spillways during this release (Fedarko, 2013)[14], and the spillways were redesigned and repaired later in 1983 and in 1984.

Maximum releases through the river outlets depend on reservoir level, because the outlets are less efficient at lower reservoir elevation. The capacity of the river outlets is approximately 15,000 ft^3/s when the reservoir is higher than 3500 ft asl, but their maximum capacity is estimated to be only 4800 ft^3/s when the reservoir is at 3400 ft asl (Table 1).

The maximum capacity of the penstocks is approximately 31,500 ft^3/s. Total annual releases from Lake Powell only need to annually average approximately 11,400 ft^3/s to deliver the Law-of-the-River[15] mandated 8.23 million af (acre-feet) that is required to be transferred from Lake Powell in the Upper Basin to Lake Mead in the Lower Basin. Presently, the river's flow is increased during daytime and decreased at night in response to regional patterns of electricity demand, a practice known as "load-following". Topping et al. (2003) showed that the median daily range of load-following was 13,700 ft^3/s/day during the 1970s. Administrative agreements made during the past 20 years limit the daily range of reservoir releases to fluctuations no greater than approximately 8000 ft^3/s/day, and the typical average daily fluctuations are less than this. The median daily fluctuation for the 1990s was 4900 ft^3/s/day (Topping et al., 2003).

The minimum elevation at which hydropower can be produced is 3490 ft asl. Although the elevation of the penstocks is 3462 ft asl, 3490 ft asl is the lowest elevation at which reservoir water can be safely withdrawn into the penstocks, because cavitation in the turbines occurs when water is withdrawn at lower reservoir elevations. The river outlets are at 3370 ft asl. Thus, approximately 1.89 million af of water is stored below the elevation of the river outlets,

Table 1. Maximum rate of discharge through the river outlets as a function of Lake Powell elevation[20]

Reservoir elevation, in feet above sea level	Maximum discharge through river outlets, in cubic feet per second	Maximum discharge rate through by-pass tubes, in acre feet per year
3500	15,000	10,900,000
3490	14,600	10,600,000
3450	12,600	9,090,000
3440	11,400	8,280,000
3430	10,200	7,410,000
3420	8800	6,370,000
3400	4800	3,470,000

and this water cannot be released downstream; this water is considered “dead storage.”

At 3490 ft asl, the water surface area of Lake Powell is approximately 77 mi^2, which is 31% of the surface area when the reservoir is full (3700 ft asl) which is approximately 251 mi^2 (Fig. 3). The water surface area of Lake Powell at dead pool is approximately 32 mi^2 (Fig. 3) and is approximately 13% of the reservoir surface area when full.

2.2. Colorado River in the Grand Canyon ecosystem

The three facilities that release water downstream exist at fixed, and different, elevations. Because reservoirs stratify in temperature with warm water on the surface and cold water below in summer, the relatively low elevation at which water is withdrawn into the penstocks and river outlets results in cold water being transferred from the reservoir to the Grand Canyon ecosystem. The only times when warm reservoir water is released downstream are when the spillways are used

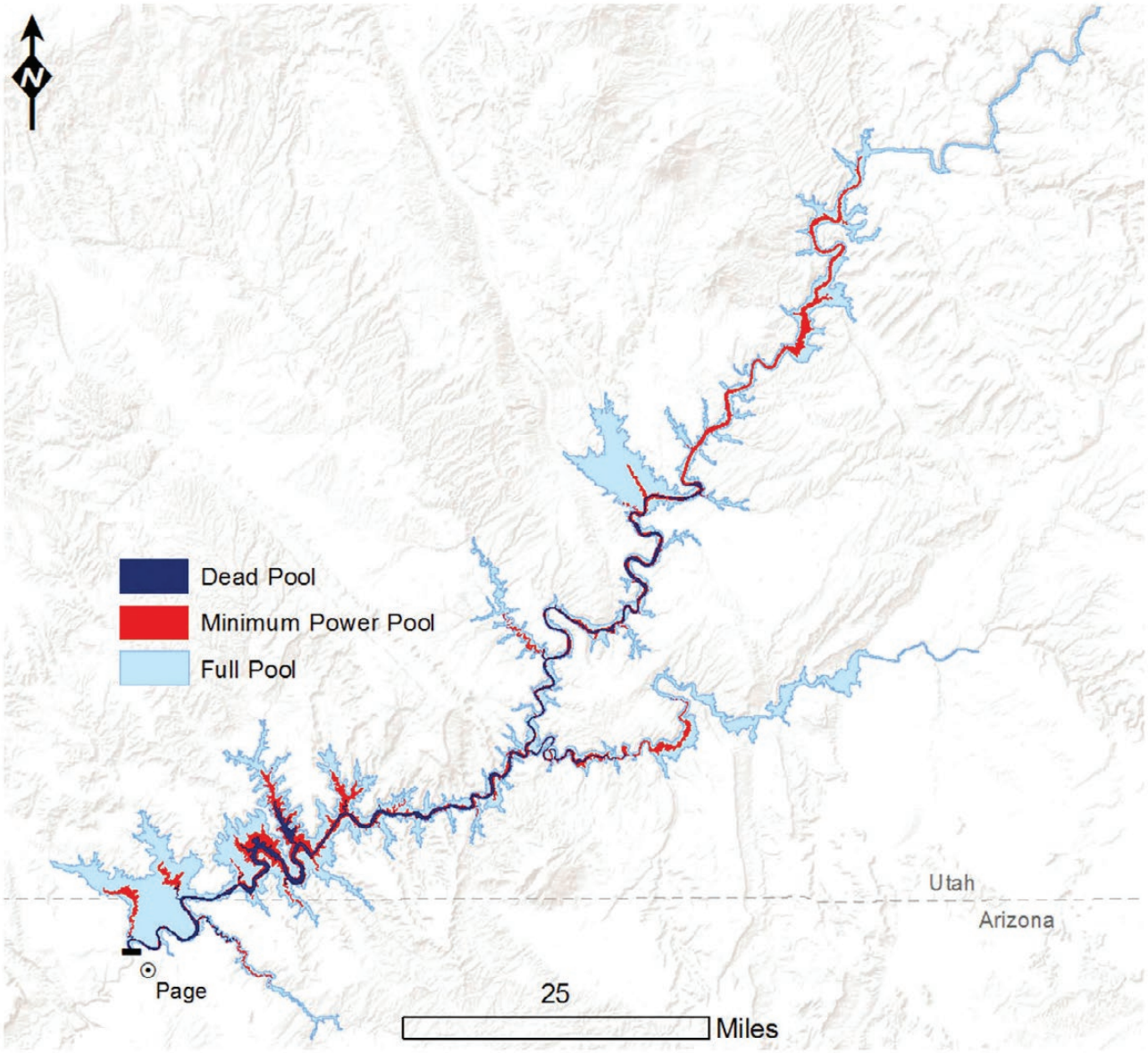


Figure 3. Map showing estimated surface area of Lake Powell at full operating pool, minimum power pool (3490 ft asl), and dead pool (3370 ft asl). This map is based on the topography as depicted by pre-reservoir topographic maps and does not depict the topography of the deltas that now exist in the Colorado River arm near Hite and in the San Juan arm.

or when the reservoir is very low. Thus, the thermal regime of the Colorado River has been changed greatly. The pre-dam river fluctuated in temperature from near freezing in winter to 80°F in summer. This annual fluctuation in temperature cued different aspects of the life history of the native fish. Following completion of the dam, the annual fluctuations in reservoir temperature gradually decreased (Fig. 4). Today when Lake Powell is relatively full, dam releases are less than 50°F and do not change significantly during the year. The cool, summer water temperatures inhibit sexual maturation of many species of main-stem, native fish. When Lake Powell is relatively low, warmer water is released downstream, and favorable temperatures for native fish reproduction sometimes exist in parts of lower Marble Canyon and in Grand Canyon; this situation occurred before 1963 and after 2003 (Fig. 4).

Nonnative fish species have been introduced into the Grand Canyon ecosystem, and some of these species prey upon or compete with native fish (Gloss and Coggins, 2005)[16]. Rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) are advantaged by relatively cold river temperatures, and both species prey upon the endangered humpback chub (*Gila cypha*). Warm-water, nonnative fish, such as smallmouth bass (*Micropterus dolomieu*), presently live in Lake Mead, and there is speculation that warmer Colorado River temperatures released from a lower Lake Powell would allow upstream invasion of these nonnatives.

The total supply of fine sediment was reduced by 99.5% at Lees Ferry and by 81-85% at the Grand Canyon gaging station located at RM 87 (Topping et al., 2000)[17]. The capacity of the Colorado River to transport fine sediment has been reduced because of the elimination of the natural spring flood, but the Colorado River is nevertheless deficient in fine sediment, because the fine sediment supply has been reduced to an even greater degree (Schmidt and Wilcock, 2008)[18]. Thus, the Colorado River in the Grand Canyon ecosystem has more capacity to transport fine sediment than there is fine sediment available to transport. In response, the Colorado River incised its bed in Glen Canyon by as much as 5 ft (Grams et al., 2007)[19], and sand bars in Marble and Grand Canyons were eroded (Schmidt and Grams, 2011)[20].

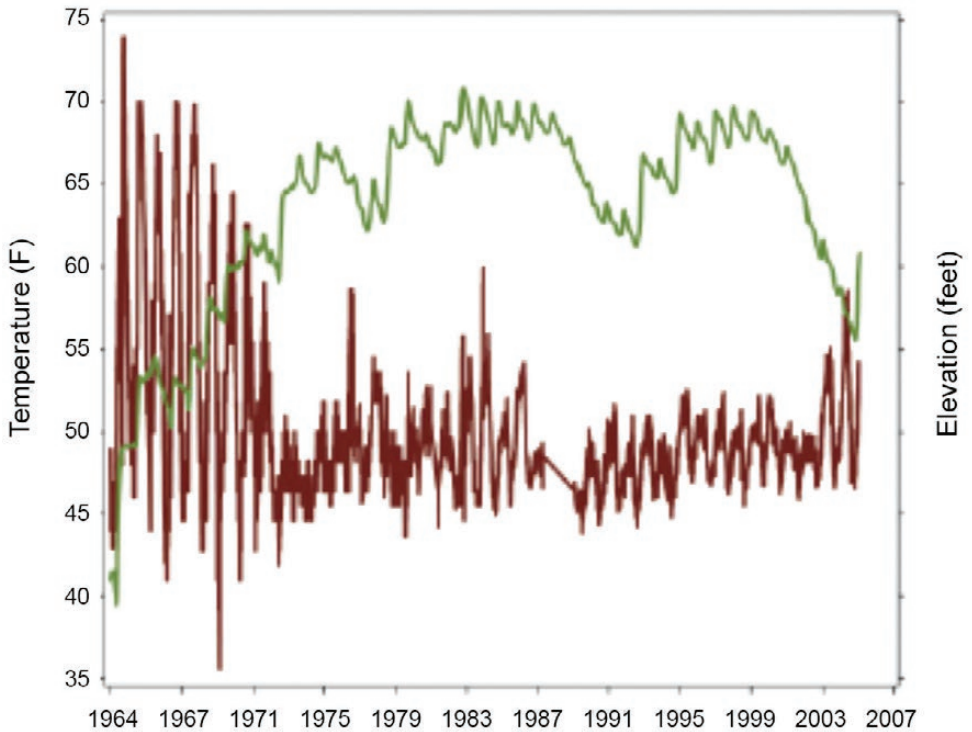


Figure 4. Graph showing Lake Powell elevation (green) and temperature (red) of the Colorado River at Lees Ferry between 1963 and March 2016 (Vernieu et al., 2005, figure 6).

3. Issues Associated with Implementation of the Fill Mead First Plan

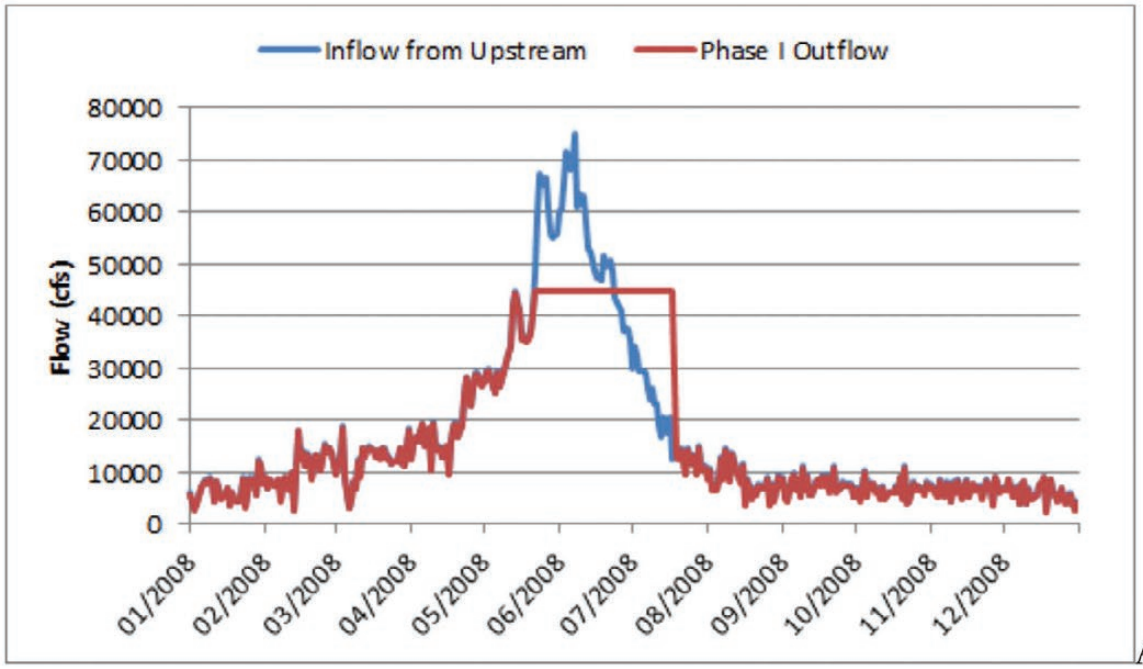
The existing FMF plan has only been described in a conceptual way (Kellett, 2013). Here, we summarize these phases, and we identify some critical uncertainties and operational issues that would have to be described if the plan is to be fully evaluated.

3.1. Phase I ("Initial Scenario"): Lake Powell is drained to minimum power pool elevation.

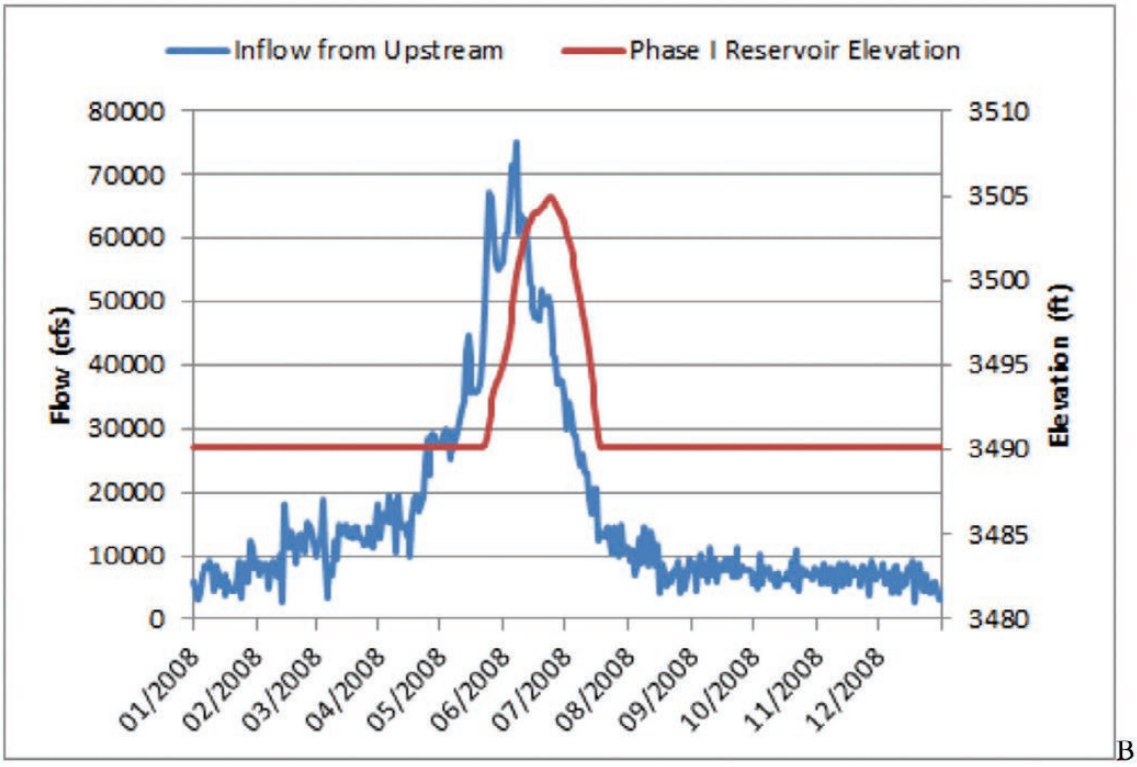
In this initial phase, Lake Powell's elevation would be lowered to 3490 ft asl (Kellett, 2013). Thus, Phase I does not require construction of new infrastructure to release reservoir water, because the penstocks and river outlets would remain functional.

Although 3490 ft asl might be the target elevation for Phase I, Lake Powell would unavoidably fluctuate in elevation throughout the year, rising during the snowmelt runoff season and falling thereafter. The magnitude of the annual rise would be greater in years of large inflows and less, or not at all, in dry years. This annual fluctuation in reservoir elevation would occur, because reservoir releases could not precisely mimic the natural flood regime. The incoming spring flood will exceed the capacity to release reservoir water downstream in most years, because the maximum release from Lake Powell at these lower elevations is ~45,000 ft^3/s. Thus, implementation of Phase I would require Reclamation to establish an operating rule concerning how water would be released during the season of high inflows.

Here, we assume that Reclamation would implement a rule wherein the duration of 45,000 ft^3/s releases would be sufficiently long to return Lake Powell to the target elevation as quickly as possible. The implication of this reservoir operations strategy during a year of relatively large inflows is illustrated in Figure 5, using the inflow conditions of 2008 when inflow was ~12 million af. Based on this volume of inflow, reservoir elevation would increase by approximately 15 ft and be above 3490 ft asl for approximately 6 weeks (Fig. 5B). Downstream releases of 45,000 ft^3/s would continue for about 2 weeks longer than the duration of the incoming flood (Fig. 5A) in order to drain the reservoir back to 3490 ft asl quickly.



A



B

Figure 5. Graphs showing (A) Outflows under Phase I of FMF if the daily inflows were those that occurred in 2008, based on modeling and assumptions described in text. (B) Predicted reservoir elevation for the same conditions.

We assume that reservoir releases during the rest of the year would mimic inflows. Thus, hydropower revenue could not be maximized, because the greatest amount of electricity would be produced during the spring snowmelt season when reservoir outflows would be the greatest. However, demand for hydroelectricity is relatively low at that time. The least amount of electricity would be produced during winter when reservoir inflows would be lowest, but demand is relatively high at that time of year. Reclamation would be challenged to keep the power plant operational if the target reservoir elevation was precisely at 3490 ft asl, because the penstocks would have to be closed whenever reservoir stage dropped below that elevation. It would be an operational challenge to maintain a fixed reservoir elevation with only a small tolerance for unexpected decreases in inflow. Thus, it is likely that a target reservoir elevation higher than 3490 ft asl would be implemented in order to allow operational flexibility in the release of reservoir water downstream.

Another critical issue that would have to be addressed would be the way in which Lake Powell would be initially drained to 3490 ft asl. We assume that the duration of time of initial draining of Lake Powell would be a few years, and this would partly depend on the contents of Lake Powell and of Lake Mead at the time FMF was implemented. We assume that drainage of the reservoir would be accomplished in a manner consistent with Law-of-the-River requirements regarding delivery of water from the Upper Basin to the Lower Basin, environmental attributes and issues of the Grand Canyon ecosystem, and health-and-safety issues throughout the Lake Powell area.

A partially drained Lake Powell would extend for approximately 155 mi throughout all of Glen Canyon to the base of the reservoir's delta near Hite. The upper surface of the reservoir delta in Cataract and Narrow Canyons would be exposed.

3.2. *Phase II: Lake Powell is drained to dead pool elevation.*

In Phase II of FMF, Kellett (2013) proposed that Lake Powell would be drained to dead pool elevation of 3370 ft asl, and hydropower production would be abandoned. Although GCI asserts that run-of-the-river conditions would thereafter prevail, reservoir water could only be released through the river outlets, because water could not be withdrawn into the penstocks. By definition, there would be no active storage, although Lake Powell could be used to store water if Lake Mead were to fill, such as when a succession of wet years occurred.

The relatively small capacity of the river outlets would make it impossible for the flow regime of the Colorado River in the Grand Canyon ecosystem to resemble the pre-dam, natural regime. Instead, stream flow in the Grand Canyon ecosystem would be 15,000 ft^3/s or less and would be steady throughout the day. During the spring snowmelt season, however, inflows would greatly exceed the capacity to release water downstream, and the elevation of Lake Powell would increase greatly. We analyzed likely reservoir releases and changes in reservoir elevation during the same hypothetical inflow scenario analyzed in Phase I. Reservoir releases could only be 15,000 ft^3/s during the initial weeks of flood inflows to Lake Powell (Fig. 6A), and the elevation of Lake Powell would rise by more than 100 ft (Fig. 6B). Once the reservoir rose to 3490 ft asl, water could be released into the penstocks, and we assume that a controlled flood of approximately 45,000 ft^3/s would be released downstream for as long as Lake Powell remained above 3490 ft asl. Based on the hypothetical inflow scenario of 2008, a month-long controlled flood of approximately 45,000 ft^3/s would begin approximately 6 weeks after the rise of the natural flood that entered Lake Powell. Based on the scenario of 2008, it would not be possible to fully drain Lake Powell back to dead pool elevation by the end of the calendar year, because of the relatively small capacity of the river outlets (Table 1).

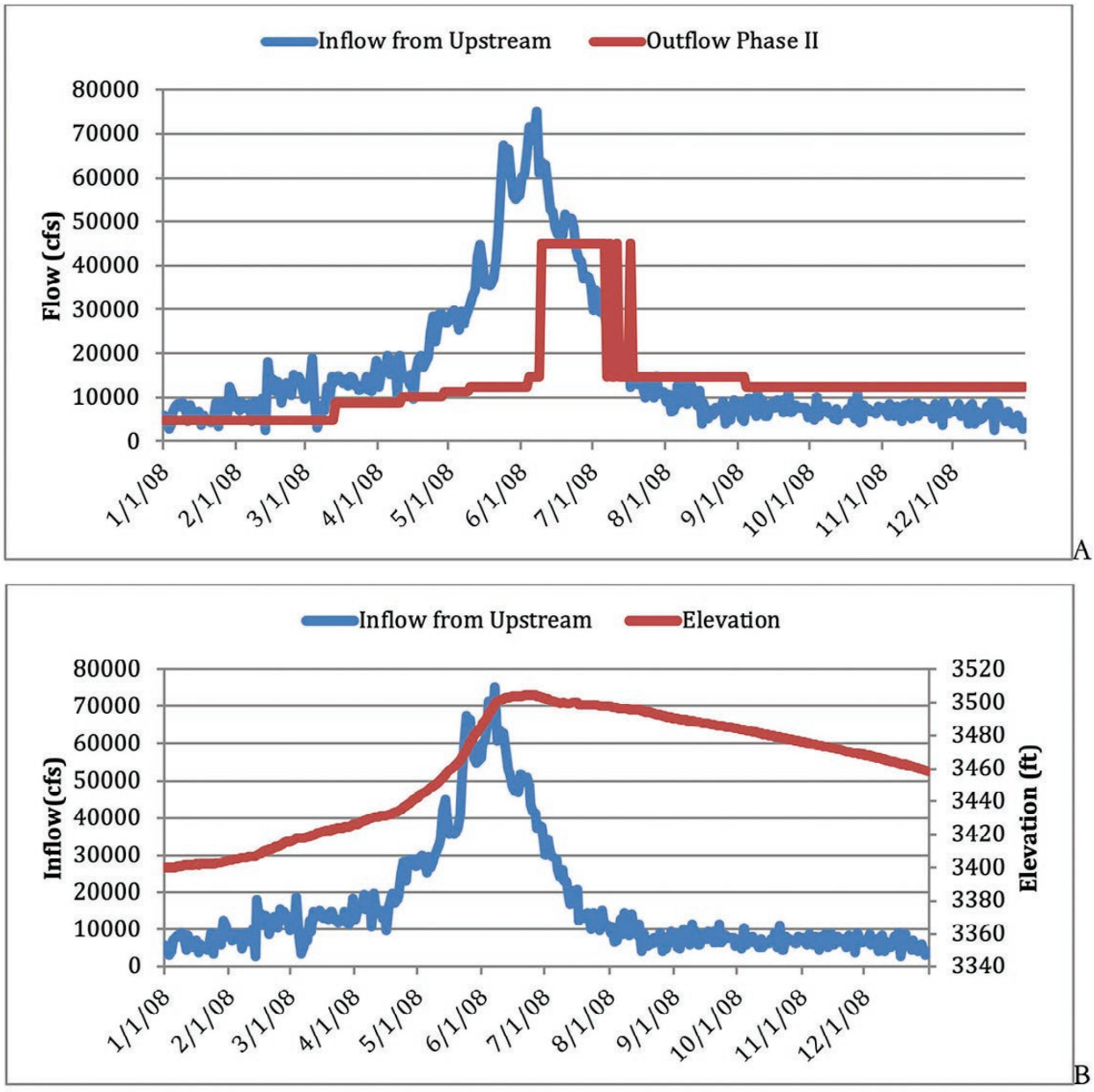


Figure 6. Graphs showing (A) Outflows under Phase II of FMF if the daily inflows were those that occurred in 2008, based on modeling and assumptions described in text. (B) Predicted reservoir elevation for the same conditions.

No electricity would be generated when flow was confined to the river outlets unless new turbines were constructed on those structures. Electricity could be generated when reservoir stage temporarily reached minimum pool elevation, but it is unknown whether the Glen Canyon Dam turbines could be operated in such an intermittent way, nor is it known how or if such electricity could be marketed.

3.3. Phase III: New diversion tunnels are drilled so that the entire flow of the Colorado River passes around Glen Canyon Dam.

Under Phase III, new diversion tunnels would be drilled into the Navajo sandstone that surrounds the dam. These diversion tunnels would allow incoming floods to flow around the dam. Reclamation considered undertaking such an effort in the 1970s in the context of increasing hydropeaking capacity of the dam, and the agency proposed installing turbines on newly drilled tunnels (Bureau of Reclamation, 1977)[21]. Among many possibilities, Reclamation (1978, p. 28)[22] considered the "Lees Ferry Modification" plan wherein "new penstocks … are anticipated to be drilled through plugs in the old diversion tunnels used during construction of Glen Canyon Dam." Reclamation (1978) proposed that the total capacity of these turbines constructed at the outlets of 4 newly drilled 22.7-ft diameter tunnels would be 32,300 ft^3/s; other design strategies could be implemented in the future. Although the actual costs of this project were not reported, benefit-cost ratios were reported (Reclamation, 1978, exhibit 2), suggesting that preliminary cost estimates for drilling these tunnels were made.

It is impossible to speculate on the capacity of any new diversion tunnels that might be drilled as part of Phase III, because the construction of new tunnels would have to be based on detailed engineering and cost studies. Reclamation (1978, p. 28) also recognized this and stated, "Foundation conditions at Glen Canyon Dam would need to be examined." Although the reports published in the late 1970s demonstrate that the idea of drilling new diversion tunnels is possible, the costs associated with such an effort might be substantial.

It is impossible to estimate what would be the magnitude and frequency of future floods that might pass through these tunnels, and on-going climate change has the potential to increase year-to-year variability, despite an overall decrease in total annual runoff (Bureau of Reclamation, 2012)[23]. In the event a future flood exceeded the capacity of the diversion tunnels, water would temporarily be impounded within the former Lake Powell, because it is unlikely that new diversion tunnels would be sufficiently large to be able to pass all conceivable future floods. Topping et al. (2003) estimated that floods with a peak discharge of about 50,000 ft^3/s occurred every year on average prior to construction of Glen Canyon Dam and that floods of about 125,000 ft^3/s occurred every 8 years, on average.

3.4. Findings

The only way to release reservoir water from a partially drained Lake Powell is through the penstocks or through the river outlets. The maximum discharge of a flood released from Glen Canyon Dam under Phase I of FMF would be ~45,000 ft^3/s, which is less than the magnitude of most of the annual floods that occurred before Glen Canyon Dam was completed. If Phase II of FMF was implemented, reservoir water could only be released through the river outlets; the maximum release would be ~15,000 ft^3/s. Whenever inflows exceeded the capacity to release water downstream, Lake Powell would partially refill and the rate of draining the reservoir would depend on whether the reservoir level reached the elevation at which the penstocks could be used to supplement releases from the river outlets. ***For purposes of public policy discussion, the likely reservoir release patterns from a partially drained Lake Powell should not be assumed to mimic the natural flow regime of the Colorado River. If Phase II of FMF was implemented, stream flow of the Colorado River in Grand Canyon would be nearly constant when water accumulated in the reservoir each spring after the snowmelt flood entered the reservoir from upstream.*** In the 1970s, Reclamation made conceptual proposals to drill new diversion tunnels at Glen Canyon Dam in order to increase hydropower production. ***GCI's Phase III proposal for FMF is similar to this earlier proposal and is probably the only way that a natural flow regime could be re-established in the Grand Canyon.***

4. Would the Fill Mead First Plan Save Water?

It is unlikely that the FMF plan, or any other water storage plan that is an alternative to the present equalization rule, would be implemented unless the plan would increase the net supply of Colorado River water available for consumptive or environmental purposes. GCI asserts that implementation of FMF would save as much as ~0.30 million af/yr (acre feet per year) of water (Graham, 2013)[24]. This assertion is based on Myers' (2010[25], 2013a[26],b[27]) estimate that losses associated with storage of ground water in the Navajo sandstone that surrounds much of Lake Powell are larger than presumed increased evaporation losses that would occur if water was preferentially stored in Lake Mead. Here, we review previous studies of evaporation losses on each reservoir and suggest that these losses might decrease if FMF were implemented. However, the uncertainty in estimating evaporation rates is large, and the uncertainty is greater than the difference between the estimated total evaporation losses associated with the present management scheme and those that would occur if FMF were implemented. We also find that the uncertainty associated with estimation of reduced ground-water storage losses from Lake Powell are likely to have been overestimated.

We argue that new measurement programs should be implemented at this time so that the uncertainty in evaluating the FMF plan can be reduced. We conclude that a new measurement program of evaporation rates from Lake Powell based on modern theory and measurement technology ought to be initiated, because no measurements have been made since the 1970s. We also conclude that monitoring data concerning ground-water conditions surrounding Lake Powell ought to be analyzed, because such analysis has not occurred since the mid-1980s. New observation wells ought to be drilled further from Lake Powell to detect changes in ground-water conditions, and an analysis ought to be conducted of conditions south from Lake Powell. An analysis of ground-water storage changes surrounding Lake Mead also ought to be conducted. Data from these studies will be essential to make informed decisions about how to manage Lake Powell and Lake Mead in the future.

4.1. The role of water budgets in estimating losses

4.1.1. Overview

Budgets of any kind, including water budgets, are a fundamental tool in many scientific investigations. In the case of a reservoir, a water budget represents the amount of water entering and leaving the reservoir and is

$$\Delta S = I + P - E \pm G - R - D \qquad (1)$$

where ΔS is the change in reservoir storage, I is all surface waters that enter the reservoir, P is the precipitation that falls directly on the reservoir, E is the total evaporation from the reservoir, G is the amount of ground-water storage that occurs by water entering or exiting the reservoir into the surrounding bedrock and/or unconsolidated deposits, R is the surface water that is released from the reservoir, and D is any direct withdrawal of water from the reservoir. Water budgets have long been a fundamental tool in analyzing the hydrology of Lake Mead and Lake Powell.

Ground-water storage is an inevitable result of creating a reservoir. Water moves into surrounding bedrock and unconsolidated deposits whenever the reservoir elevation rises above the potentiometric surface[28] of the surrounding ground-water system. The ultimate fate of this water is uncertain, having the potential to irreversibly flow away from the reservoir (called "bank seepage") or to temporarily accumulate and move in and out of the surrounding bedrock when the reservoir rises or falls (called "bank storage"). The duration of "temporary storage" can range from months to centuries, depending on the hydraulic characteristics of the surrounding geologic formations and the duration of time the reservoir is relatively full or empty. Thus,

$$G = \pm G_{storage} - G_{seepage} \qquad (2)$$

where $G_{seepage}$ is bank seepage and $G_{storage}$ is bank

storage. Where $G_{storage}$ fluctuates for periods of decades to centuries, the stored water is not relevant to year-to-year water-supply management. Where $G_{storage}$ exits or enters the reservoir during short time periods, storage can be a positive or negative term and is relevant to water-supply management. We distinguish between these two time scales of bank storage as $G_{storage:long}$ and $G_{storage:short}$, respectively. Thus,

$$G = \pm G_{storage:short} - G_{storage:long} - G_{seepage} \quad (3)$$

In the case of Lake Powell, a water budget representing the amount of water that enters and leaves the reservoir is

$$\Delta S_{LP} = CR_C + GR_{GR} + SJR_B + \sum tribs_{ungaged} + P - E - G_{seepage} - G_{storage:long} \pm G_{storage:short} - CR_{LF} \quad (4)$$

where ΔS_{LP} is the change in water storage in Lake Powell for a specified period of time, CR_C is stream flow measured at USGS gage 09180500 (Colorado River near Cisco, UT), GR_{GR} is stream flow measured at USGS gage 09315000 (Green River at Greenriver, UT), SJR_B is stream flow measured at USGS gage 09379500 (San Juan River near Bluff, UT), $\sum tribs_{ungaged}$ is the total stream flow that enters the Colorado, Green, or San Juan Rivers in the watershed that drains to points downstream from the respective gages or directly into Lake Powell, and CR_{LF} is the stream flow measured at USGS gage 09380000 (Colorado River at Lees Ferry). Water that enters the surrounding bedrock and returns to the Colorado River in the 15 mi between Glen Canyon Dam and the Lees Ferry gage is bank seepage, because that water is irreversibly lost from the reservoir. However, this water is not lost to downstream Colorado River users or to the river ecosystem, because it re-enters the Colorado River.

A water budget for Lake Mead is similar to (4), except that the measured points of inflow and outflow of the Colorado River and its tributaries differ

$$\Delta S_{LM} = CR_I + \Sigma tribs_{gaged} + \sum tribs_{ungaged} + P - E - G_{seepage} - G_{storage:long} \pm G_{storage:short} - D_N - CR_{HD} \quad (5)$$

where ΔS_{LM} is the change in water storage in Lake Mead for a specified period of time, CR_I is the gaged inflow of the Colorado River in the Grand Canyon, $\Sigma tribs_{gaged}$ is the measured flow of large tributaries downstream from the point of measurement of the Colorado River or of tributaries that flow directly to Lake Mead, $\sum tribs_{ungaged}$ is the total stream flow of other tributaries, D_N is the direct withdrawal of water from Lake Mead by the state of Nevada, and CR_{HD} is stream flow measured at USGS gage 09421500 (Colorado River below Hoover Dam). The point of measurement of CR_I has changed over time: originally this measurement point was USGS gage 09402500 (Colorado River near Grand Canyon, AZ), but a gage was installed in 2007 that is 138 mi closer to Lake Mead (USGS gage 09404200; Colorado River above Diamond Creek near Peach Springs, AZ). The location of inflow from the Virgin River has also changed.

4.1.2. Estimating losses using water budgets

Although the water budget equations described above precisely account for all inflows and outflows, there is substantial uncertainty in estimating some of the terms in (4) and (5), especially $\sum tribs_{ungaged}$, E, P, and each part of G. As described below, E is typically measured by multiplying the rate of evaporation times the surface area of the reservoir. Although the surface area of the reservoir is precisely known, there is substantial uncertainty in estimating the evaporation rate. By definition, $\sum tribs_{ungaged}$ is not measured and is estimated by indirect means. P is not directly measured, and is either estimated from measured rainfall at weather stations or is assumed to be constant from year to year. G is typically computed as the residual of the other terms in (1). In other words, (1) is rearranged so that all other quantities are on the right side of the equation, and G is computed by

$$G = I + P - E - R - D - \Delta S \quad (6)$$

Meyers (2010, 2013a) used a version of (6) to estimate G, but some of the terms on the right side of (6) nevertheless have large uncertainty. We summarize the results of field and numerical modeling studies that measured ground-water elevations and flow rates at wells and springs surrounding Lake Powell and Lake Mead, because these studies provide direct evidence of the magnitude of each part of (3) and provide an independent check on Meyers' (2013a) conclusions.

Evaluation of the efficacy of FMF depends on determining if the losses from Lake Mead are larger or smaller than the losses from Lake Powell, where:

$$losses = E + G_{seepage} + G_{storage:long} \quad (7)$$

The challenge in using (7) in policy discussion of the water-balance effects of FMF for either Lake Powell or Lake Mead is that $G_{storage:short}$ must be distinguished from the sum of $G_{seepage}$ and $G_{storage:long}$.

4.1.3. Use of water budgets by Reclamation in long-range planning and short-term operations

Reclamation no longer uses a strict water budget approach for purposes of planning annual and monthly operations of Lake Powell in the agency's constantly updated 2-year planning cycle called the 24-month study. In 2011, Reclamation abandoned use of (4) in planning releases from Glen Canyon Dam, because the uncertainties associated with the poorly constrained or unmeasured parameters introduced unacceptable uncertainty into predictions of future storage contents of the reservoir. As of March 2011, the strategy used by Reclamation in the 24-month planning study program is to use a deterministic model that projects reservoir elevations, storage, and releases as functions of the forecasted inflow, planned hydropower generation, and measurements of changes in reservoir elevation. Nevertheless, Reclamation still uses variations of (4) and (5) in the Colorado River Simulation System (CRSS) model. The CRSS model is a representation of much of the Colorado River system, including most of its reservoirs and points of diversions The CRSS is used in long-term planning, such as evaluating alternative management policies and operating criteria and in forecasting energy production (Zagona et al., 2001)[29]. CRSS was used to evaluate policy alternatives of the Interim Shortage Guidelines (Bureau of Reclamation, 2007)[30] and in developing management scenarios of the Colorado River Water Supply and Demand Study (Bureau of Reclamation, 2012). CRSS operates on a monthly time step.

4.2. *Water budget analysis of Myers (2010, 2013a,b)*

Myers (2013b) estimated that the FMF plan will save between 0.3 and 0.6 million af/yr, which was consistent with his earlier estimate (Myers, 2010) that the plan will save ~0.55 million af/yr. These estimates were based on comparing the estimated values for E, $G_{seepage}$, and $G_{storage:long}$ for Lake Powell and for Lake Mead under the present equalization rule with those estimated under the FMF plan. Based on the data presented by Myers (2010) and revised by Myers (2013a), and based on the logic presented by Myers (2013b), the estimated range of water-loss savings should have been reported as between 0.2 and 0.3 million af/yr. However, this estimated range in savings is based on assuming that evaporation rates from Lake Mead are higher than current estimates and that future rates of ground-water storage accumulation near Lake Powell are the same as those that occurred in the past, which is unlikely.

Myers (2010) calculated that total annual losses from Lake Powell under the present equalization rule are ~0.89 million af/yr by adding his estimate of average evaporation losses (~0.50 million af/yr) with his estimate of the long-term average amount of reservoir water that moves into ground-water storage (i.e., the sum of $G_{seepage}$ and $G_{storage:long}$). Myers (2010) estimated that ~18 million af of reservoir water moved into ground-water storage between 1963 and 2009 (Fig. 7), which is an average rate of ~0.39 million af/yr. Myers (2013a) reduced his estimate of the cumulative amount of ground-water storage for the period 1963 to 2009 to between ~9.6 and ~15 million af (Fig. 8)[31], which is a

long-term average rate of between 0.21 and 0.33 million af/yr (average ~0.27 million af/yr). Myers (2013a) estimated that cumulative ground-water storage had steadily increased to approximately 12 million af until 1983 (i.e., an average rate of ~0.60 million af/yr) and that movement into the surrounding ground-water system had fluctuated thereafter, increasing when the reservoir filled and decreasing when the reservoir was drawn down. By assuming that future rates of movement of reservoir water will be similar to the average rate of movement of water into ground-water storage that occurred between 1963 and 2009, Myers (2013b) estimated that the total losses (i.e., evaporation and ground-water storage) from Lake Powell are between 0.71 and 0.83 million af/yr.

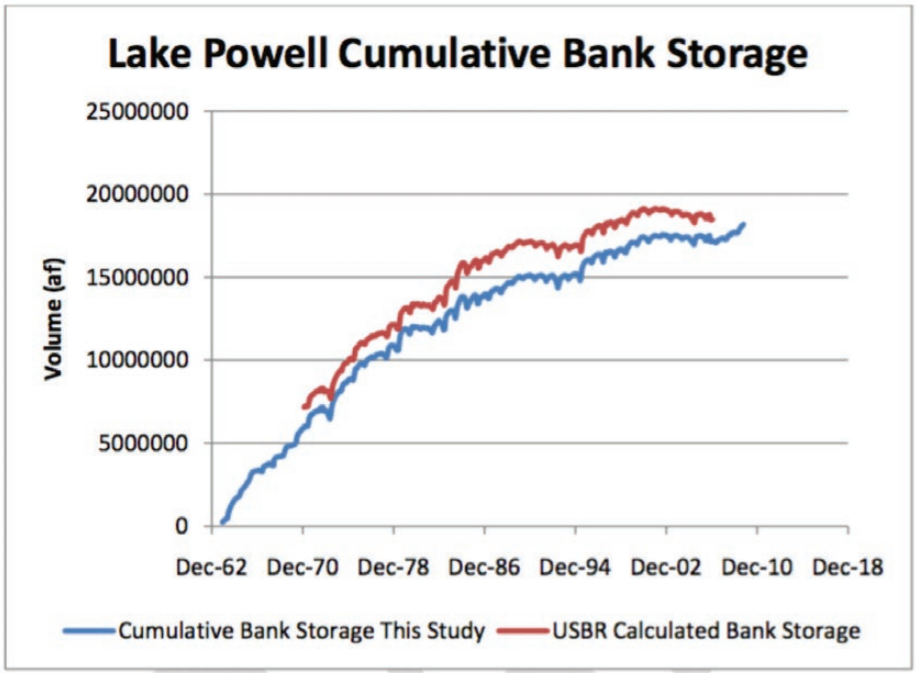


Figure 7. Graph showing cumulative bank storage (i.e., the sum of $\overline{G_{seepage}}$ and $\overline{G_{storage:long}}$) estimated by Myers (2010, noted as "this study" in the figure) and by Reclamation using a water budget approach that was used until 2011 (from Myers, 2010, fig. A8).

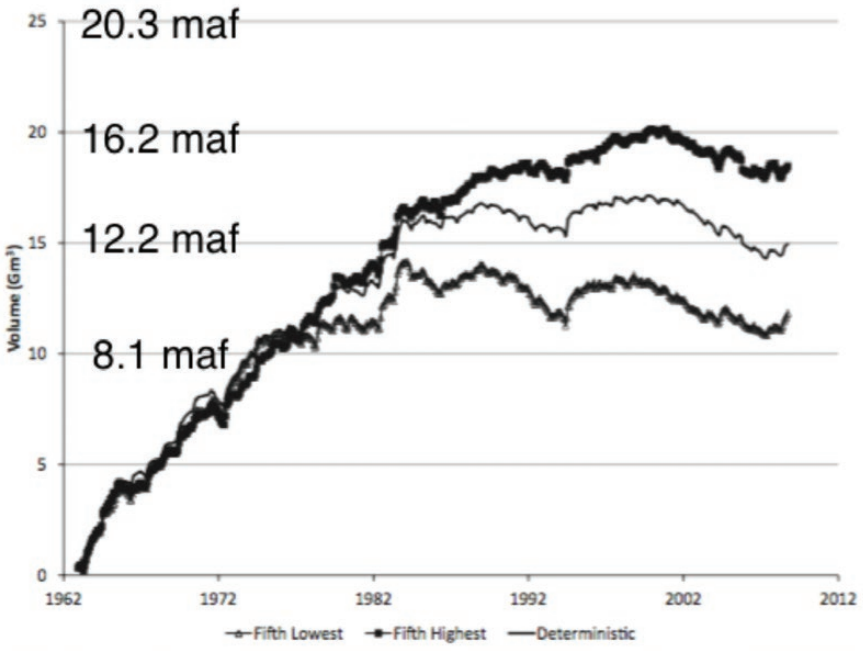


Figure 8. Graph showing cumulative bank storage (i.e., the sum of $\overline{G_{seepage}}$ and $\overline{G_{storage:long}}$) for Lake Powell estimated by Myers (2013a). Myers (2013a) used a stochastic approach to estimating the water balance of Lake Powell and the upper and lower dark lines are the 5th and 95th percentile estimates of the water balance. The inner thin black line was termed "the deterministic" estimate by Myers (2013a). This water budget indicates that the rate of progressive loss of water into the surrounding ground-water system greatly decreased in 1983.

Myers (2010, 2013b) estimated annual evaporation rates from Lake Mead to be ~0.81 million af/yr, and he estimated that ground-water storage around Lake Mead had accumulated at a rate ~ 0.070 million af/yr. Thus, Myers (2010, 2013b) estimated that the total losses from Lake Mead have been ~0.88 million af/yr; he estimated that future losses will be 0.81 million af/yr, because he asserted that ground water storage no longer accumulates. Thus, the total losses from both reservoirs associated with the present equalization rule have been between 1.6 and 1.7 million af/yr[32], and future losses will be ~0.1 million af/yr less.

GCI's estimate of water savings of implementing FMF is based on the assumption that movement of Lake Powell water into ground-water storage in the future will be at the same rate as occurred in the past. Myers (2013b) estimated that evaporation from Lake Powell at minimum power pool (i.e., Phase I) and at dead pool (i.e., Phase II) would be ~0.2 million af/yr and ~0.13 million af/yr[33], respectively. Myers (2010) estimated that ground-water storage around Lake Powell under FMF would continue to accumulate but at a very slow rate of ~0.02 million af/yr, leading to estimated total losses from Lake Powell of ~0.22 and ~0.15 million af/yr for Phase I and Phase II, respectively. Myers (2010, 2013b) assumed that the average annual evaporation losses from Lake Mead would increase to ~1.1 million af/yr, because Lake Mead will mostly be full if FMF were implemented. Thus, Myers (2013b) found that total system losses if FMF was implemented would be ~1.3 million af/yr, which would be a savings of between 0.2 and 0.4 million af/yr.[34]

Myers (2010) found that very little of the water exchanged into the surrounding ground-water system is $G_{storage:short}$, because, "Lowering reservoir water levels have not apparently caused substantial amounts of water to drain back into the reservoir." Myers (2013a) reversed his previous findings that there is no evidence of ground-water drainage back into the reservoir during periods of drawdown. He estimated that ~0.80 million af had drained back into Lake Powell between 1989 and 1995 (i.e., a rate of ~0.13 million af/yr) and that ~2.0 million af had drained back into Lake Powell between 1998 and 2008 (i.e., a rate of ~0.20 million af/yr). However, Myers (2013a) noted that far more ground water has been lost into the surrounding ground-water system than has returned during periods of reservoir drawdown.

4.3. *Previous studies of evaporation losses*

Lake Mead is approximately 2500 ft lower in elevation, and Meyers and Nordenson (1962, Plate 1)[35] estimated that the average annual evaporation rate for the Lake Mead area is 6.8 ft/yr and is 4.5 ft/yr in the Lake Powell area. Reservoir evaporation is ultimately caused by the net radiation to the reservoir, which is the difference between the amount of incoming shortwave solar radiation and the amount of longwave radiation reflected or emitted back into the atmosphere. Some of the net radiation converts water from liquid to its vapor phase, which is the process of evaporation.

Reservoir evaporation is difficult to directly measure. Evaporation is directly measured in *evaporation pans*, but the conditions in these pans are not directly comparable to reservoirs. Evaporation is indirectly estimated if the other terms of the *water budget* represented by equation (1) are known; in this case, G is often ignored. Evaporation is sometimes estimated by the *mass transfer* method where evaporation is assumed to be a function of the difference between the vapor pressure of the air above the reservoir and the saturation vapor pressure of that air, as well as the speed of the winds above the reservoir; in this case, evaporation is predicted to be greatest where windy air is hot and dry. Evaporation is also estimated using an *energy budget* approach, especially using the Bowen ratio to estimate the proportion of the net radiation that causes evaporation. The most accurate method to measure evaporation is the recently developed *eddy covariance* method where the flux of water vapor emitted from the reservoir surface is directly measured. Many of these methods demonstrate that evaporation rates may be higher when reservoirs are relatively full, because their water surfaces are typically more exposed to winds and that evaporation rates are less where the stored water is cool. There can be significant year-to-year variation in evaporation due to differences in wind, cloudiness, the temperature of the

incoming water, and the temperature of the water released from the reservoir.

The volume of water evaporated from a reservoir is calculated by multiplying the evaporation rate times the surface area of the reservoir. Lake Powell has a slightly larger surface area for the same volume of stored water. For example, the surface area of Lake Powell is 7% more than the surface area of Lake Mead when each reservoir is nearly full (Fig. 9).

Theory, measurement, and computation techniques have changed during more than 60 years since the first estimates of evaporation from Lake Mead were made. The earliest estimate of evaporation rates from Lake Mead was by Anderson and Pritchard (1951)[36] who estimated that 5.3 ft/year was lost. Detailed studies using water budget and mass transfer methods were conducted by Harbeck et al (1958)[37] who calculated that gross evaporation was 7.1 ft during water year 1953 and that 875,000 af had evaporated from the reservoir in that year. Based on correlation with evaporation

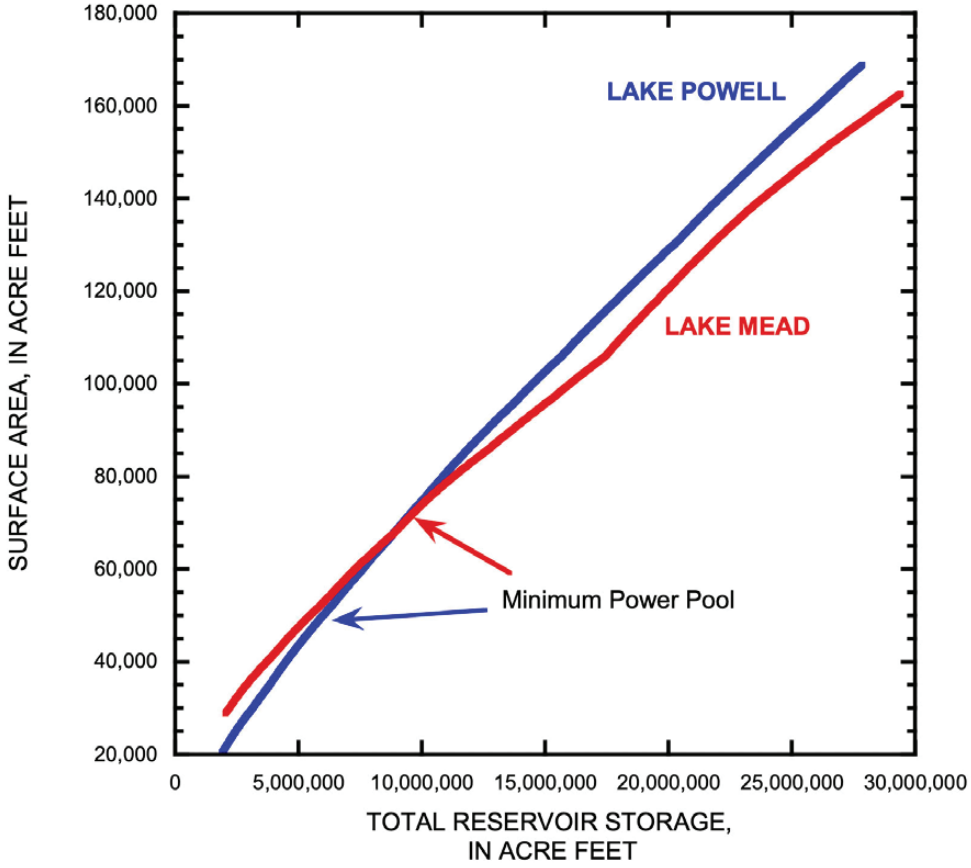


Figure 9. Graph showing the surface area of Lake Powell (blue) and of Lake Mead (red) in relation to the volume of stored water, which is the total volume of water in the reservoir. Each relationship is truncated at the volume of dead pool storage. The volume of water stored in Lake Mead at minimum power pool storage is greater than at Lake Powell. Data are from Reclamation (2007, Appendix A, Attachments B-1 and B-2).

Table 2. Evaporation rates for Lake Powell and Lake Mead, measured in different studies and for different time periods.

Month	Monthly evaporation rate (feet/month), unless otherwise noted. Values in parentheses are range during the measurement period.							
	Lake Powell			**Lake Mead**				
	Effective evaporation rate[45]	1962-1975[46]	1965-1979[47]	CRSS	1953-1973 [38]	1974-1994 [38]	1997-1999 [38]	March 2010 – February 2015[48]
January	.22	.17 (.17)	.24 (.16-.37)	0.36	.36	.30	.34	.31 (.25-.39)
February	.28	.18 (.12-.21)	.19 (.07-.27)	0.33	.30	.29	.35	.29 (.21-.39)
March	.23	.27 (.22-.32)	.29 (.23-.41)	0.37	.40	.33	.63	.30 (.19-.35)
April	.36	.38 (.31-.46)	.38 (.33-.52)	0.46	.48	.38	.63	.43 (.37-.55)
May	.43	.44 (.31-.50)	.50 (.38-.65)	0.58	.54	.52	.80	.55 (.46-.66)
June	.63	.63 (.55-.74)	.63 (.53-.83)	0.67	.67	.60	.78	.65 (.57-.80)
July	.60	.77 (.69-.93)	.70 (.53-1.0)	0.80	.76	.71	.78	.62 (.53-.86)
August	.70	.77 (.64-.93)	.77 (.62-.92)	0.85	.79	.72	.73	.69 (.49-.97)
September	.71	.72 (.63-.81)	.69 (.48-1.0)	0.70	.73	.61	.77	.66 (.56-.80)
October	.37	.53 (.47-.68)	.52 (.24-.68)	0.51	.65	.60	.69	.66 (.59-.71)
November	.36	.49 (.40-.57)	.41 (.26-.59)	0.51	.53	.54	.56	.57 (.43-.74)
December	.34	.45 (.45)	.36 (.25-.52)	0.44	.47	.42	.42	.46 (.35-.59)
Annual Evaporation Rate (feet/year)								
Annual rate	4.0	5.8 (5.2-6.3)	5.7 (4.9-6.5)	6.6	6.7	6.0	7.5	6.4 (5.9-7.2)

pan data collected near Hoover Dam, Harbeck et al. (1958) estimated that the average annual gross evaporation rate between 1941 and 1953 had been 7.0 ft/year. They provided methods by which evaporation could be estimated based on meteorological measurements made from a barge in Boulder Bay and at the Las Vegas airport, and these data were used to estimate evaporation between 1953 and 1995. The average evaporation rate for that period was 6.3 ft/year, or 791,000 af/year based on an assumed average water surface area of 126,000 acres. Westenburg et al. (2006) [38] summarized these estimates and showed that evaporation rates were higher and less variable between 1953 and 1973 than between 1974 and 1994 (Table 2).

Westenburg et al. (2006) initiated a new evaporation measurement program using the energy budget method using data collected at 4 barges in different parts of Lake Mead between 1997 and 1999; they estimated that the annual gross evaporation rate was 7.5 ft/year during that 2-year period (Table 2). Moreo and Swancar (2013)[39] used the eddy covariance technique to compute evaporation and reported on measurements made between March 2010 and February 2012; Moreo (2015) reported on measurements made between March 2010 and April 2015. Moreo (2015) found that annual gross evaporation was 6.0 ft/yr for the period between March 2010 and February 2015 and that the annual rate varied between 5.5 and 6.4 ft/yr. The lowest evaporation rate occurred between March 2013 and February 2014, and the highest rate occurred between March 2010 and February 2011. As with previous studies, Moreo (2015) found significant year-to-year variability in monthly evaporation rates (Fig. 10). In some months, the annual variability was as large as the range of all previous estimates except those of Westernberg et al (2006) whose estimates for spring were greater than of any other study.

Jacoby et al. (1977) estimated gross evaporation rates from Lake Powell between May 1973 and December 1974 using the mass transfer approach, by measuring wind and humidity at 4 barges in Lake Powell. They extrapolated their data to the

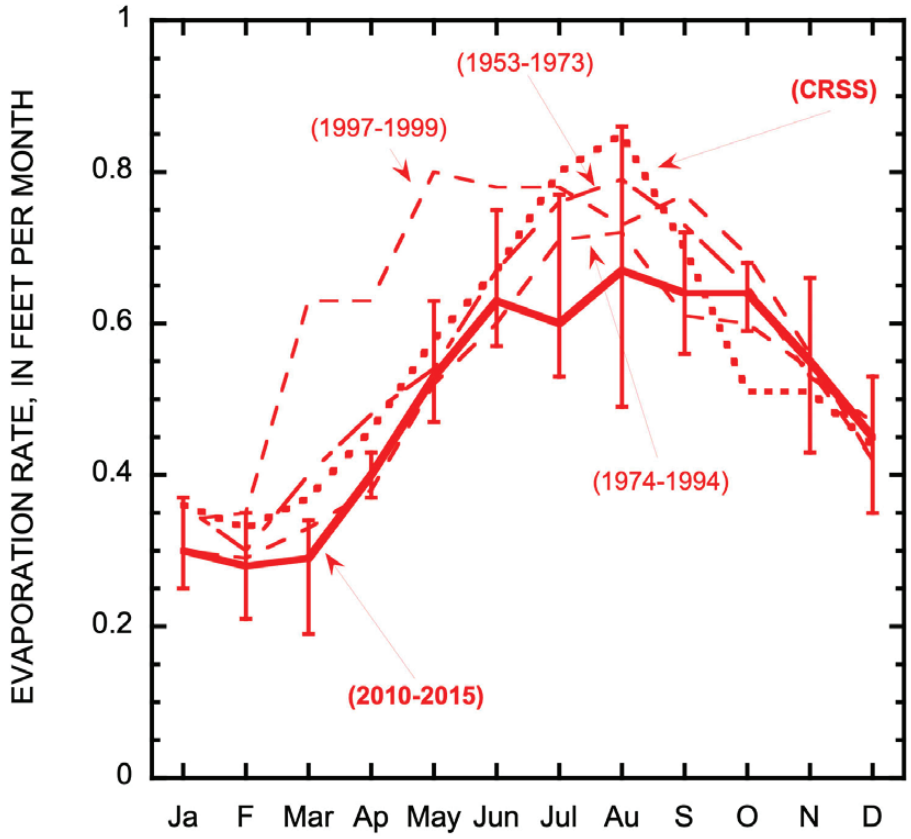


Figure 10. Graph showing monthly evaporation rates at Lake Mead measured in various studies. The most recent study (Moreo, 2015) is shown in bold solid line with error bars representing the range of measurements for the 5 years of this study. The values used in the CRSS model are shown in bold dotted line. See Table 2 and text for data sources.

period 1962 to 1975 based on correlation with evaporation pan data measured at Wahweap and estimated that the average annual gross evaporation rate for Lake Powell for this 13-year period was 5.8 ft. This estimate was higher than those by Wilson (1962)[40] who estimated the rate to be 5.5 ft/year. Jacoby et al. (1977) estimated that 724,000 af/yr was evaporated from Lake Powell assuming that the reservoir was 75% full with an average surface area of 125,000 acres. This value is 50% more than the long-term average evaporation rate assumed by Myers (2010, 2013a,b). Reclamation (1986) estimated gross evaporation between 1965 and 1979 using the same mass transfer data. Ryan (1993) summarized Reclamation's present method for calculating effective evaporation that is based on subtracting the estimated reservoir precipitation from the gross evaporation estimates (Reclamation, 1986).

For purposes of administration of the Colorado River Compact and the Upper Colorado River Compact, Reclamation also reports the "net evaporation rate," which is the gross evaporation rate minus the estimated evaporation losses that occurred from the Colorado River, its riparian vegetation, and the surrounding hillsides before construction of Glen Canyon Dam (Ryan, 1993). This value is not relevant when comparing losses from Lake Powell and Lake Mead using equation (7), and the pervasive use of "net evaporation" rates for Lake Powell causes confusion in comparing evaporation losses from the two reservoirs. Wilson (1952) estimated that the evapo-transpiration losses from the undammed Colorado River and adjacent riparian ecosystem was 227,000 af/year, but Jacoby et al. (1977) argued that this value should be 164,000 af/yr (Fig. 12).

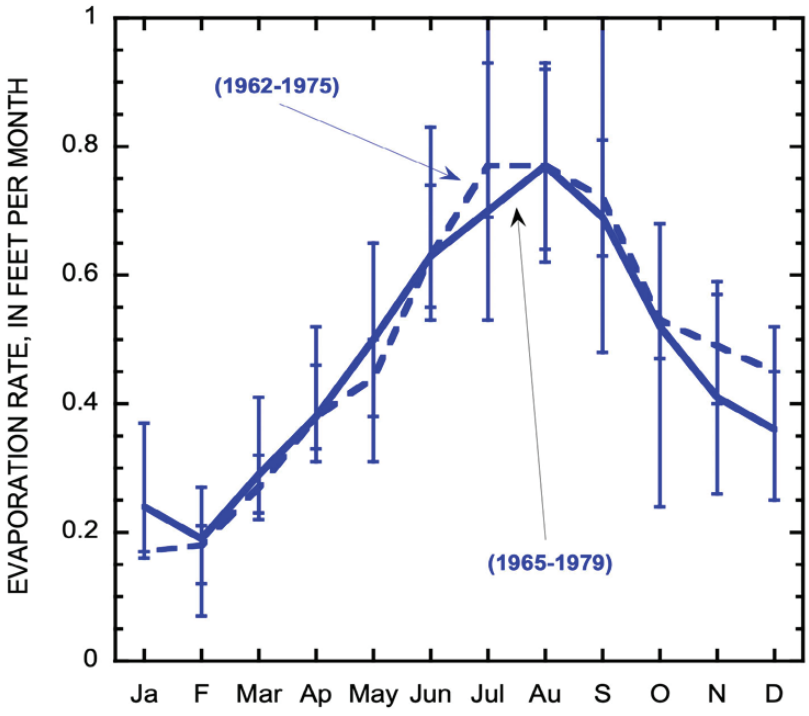


Figure 11. Graph showing monthly evaporation rates at Lake Powell as estimated by Jacoby et al (1977) for the period between 1962 and 1975 and by Reclamation (1986) between 1965 and 1979.

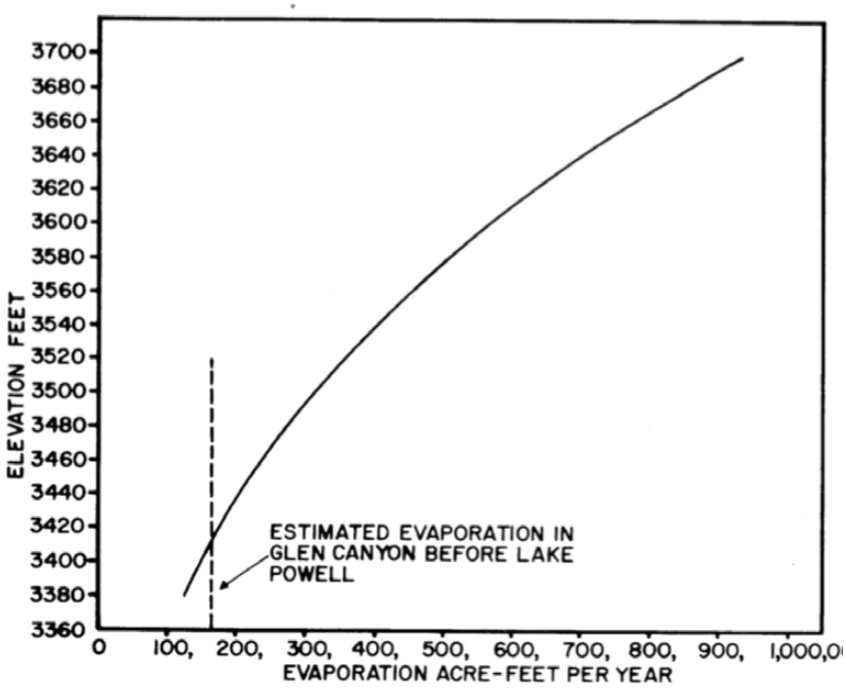


Figure 12. Graph showing the annual evaporation from Lake Powell as a function of reservoir elevation (from Jacoby et al., 1977, fig. 16).

4.4. *Evaporation losses if Fill Mead First was implemented*

If FMF is implemented, preferential storage of water in Lake Mead unavoidably would result in increased evaporation losses from Lake Mead and decreased evaporation losses from Lake Powell because of the difference in the surface areas of the two reservoirs. It is widely assumed that the increased evaporation losses from Lake Mead would exceed the decreased losses from Lake Powell, because the rate of evaporation is higher at Lake Mead. As discussed above, this may not be the case.

There is substantial uncertainty in comparing the likely evaporation losses at the two reservoirs because of the year-

to-year variability in evaporation rates at each reservoir and because of the differences in methods used to estimate evaporation. Here, we used the 5-year average evaporation rates of Moreo (2015) as the future average evaporation rate at Lake Mead, and we used the complete range in estimated annual evaporation to define the uncertainty in these estimates. We used the 15-year average evaporation rate estimated by Reclamation (1986) as the future average evaporation rate at Lake Powell, and we used the complete range in estimated annual evaporation to define the uncertainty in these estimates. We did not account for the difference between the methods used -- eddy covariance at Lake Mead and mass transfer at Lake Powell – nor did we account for the different measurement periods of the Lake Mead and Lake Powell studies.

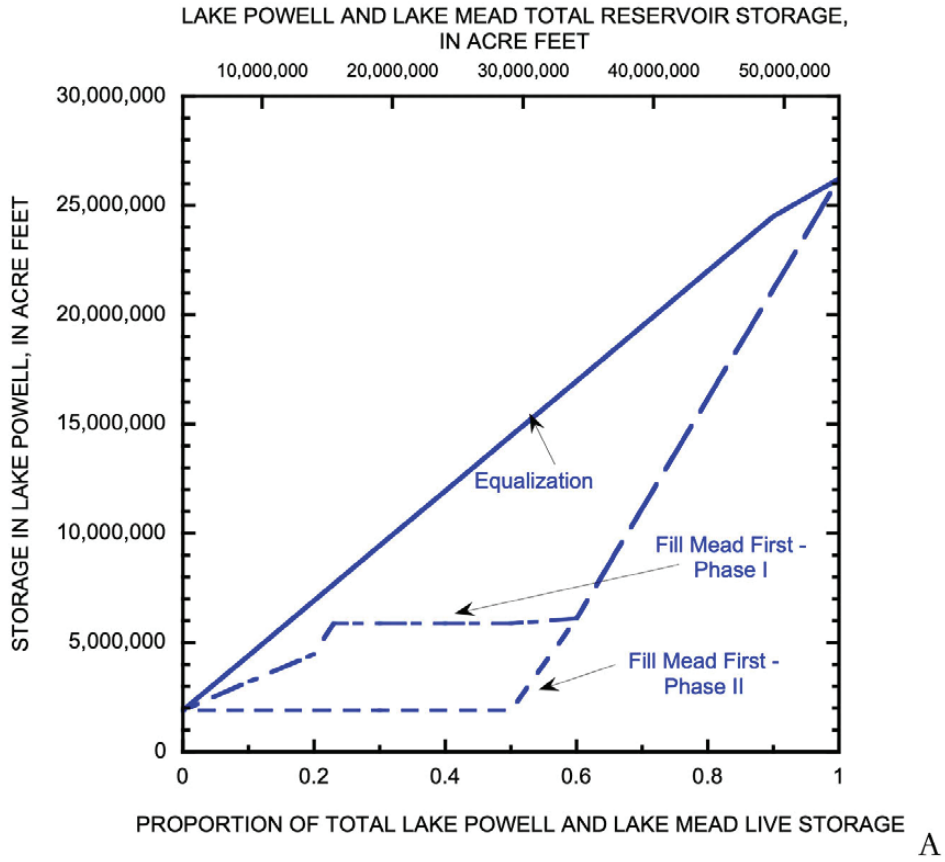
If one considers the measured range of natural variability in estimating future evaporation rates, then it cannot be demonstrated that implementation of FMF would significantly change total evaporation from the two reservoirs. The available data do not indicate that the total evaporation would increase if water is preferentially stored in Lake Mead; in fact, the available data suggest that preferential storage of water in Lake Mead might reduce total reservoir evaporation losses. The available data do demonstrate that the total surface area of the two reservoirs would be less if FMF were implemented, in comparison to the present reservoir management scheme where storage contents of the two reservoirs are equalized.

A comprehensive analysis comparing future reservoir evaporation under the present equalization rule and under the FMF plan necessitates predictions of future watershed runoff and future evaporation rates, and such an analysis is beyond the scope of this study. Predictions about the total available reservoir storage contents in the future have been made elsewhere (Barnett and Pierce, 2008[41]; Rajagopalan et al., 2009[42]). We took a simple approach and estimated evaporation under a range of total reservoir storage conditions by multiplying the available measurements of evaporation rate (Table 2) times Reclamation's (2007, Appendix A) volume-to-surface area relations for each reservoir (Fig. 9). We made assumptions about how active storage is allocated between the two reservoirs under the present equalization rule and would be allocated under FMF. We estimated reservoir evaporation for a range of conditions ranging from empty reservoirs at dead pool to full reservoirs. We assumed that the total active storage of Lake Mead is 26.0 million af and that the total active storage of Lake Powell is 24.3 million af. (Reclamation, 2007, Appendix A), thus assuming that the total active reservoir capacity of Lake Powell and Lake Mead is 50.3 million af (<http://www.usbr.gov/lc/region/g4000/weekly.pdf>). In September 2016, total active storage in the two reservoirs was 22.7 million af, which is approximately 45% of the total capacity of Lake Powell and Lake Mead. In summer 1983, reservoir storage was 52.5 million af and exceeded the stated operational capacity, because temporary flood control capacity was utilized.

We simplified the present equalization rule. We assumed that the active storage contents of the two reservoirs is the same and that the two reservoirs are filled and drained to the same degree. Although this strategy is impossible to implement in a precise operational sense, this simplification is adequate for the analysis here. We assumed that half of the total active storage (i.e., reservoir storage greater than dead pool) would be assigned to each reservoir (Table 3). For the Phase I scenario of FMF, we assumed that Lake Powell would be maintained at minimum power pool elevation (~4.0 million af of active storage) and that all other active storage would occur in Lake Mead until the point that the reservoir filled. Because active storage of Lake Mead is 9% larger than Lake Powell, Lake Mead can store slightly more than 50% of the total active storage of the two reservoirs (Fig. 13). In the event more storage is needed, we assumed the additional storage would occur in Lake Powell. For the Phase II scenario of FMF, we assumed that the elevation of Lake Powell would be maintained at dead pool and that all active storage would occur in Lake Mead until the point that the reservoir filled.

Table 3. Assumptions about how storage would be allocated in Lake Powell and Lake Mead for different management scenarios

			Present strategy -- Equalization of reservoir contents				Fill Mead First -- Phase I				Fill Mead First -- Phase II			
Total storage in Lake Powell and Lake Mead, in acre feet	Total live storage, in acre feet	proportion of total system live storage	Allocation of live storage, in acre feet		Allocation of total storage, in acre feet		Allocation of live storage, in acre feet		Allocation of total storage, in acre feet		Allocation of live storage, in acre feet		Allocation of total storage, in acre feet	
			Lake Powell	Lake Mead	Lake Powell	Lake Mead	Lake Powell	Lake Mead	Lake Powell	Lake Mead	Lake Powell	Lake Mead	Lake Powell	Lake Mead
54,196,646	50,266,646	1	24,322,365	25,944,281	26,217,365	27,979,281	24,322,365	25,944,281	26,217,365	27,979,281	24,322,365	25,944,281	26,217,365	27,979,281
49,169,981	45,239,981	0.9	22,619,991	22,619,991	24,514,991	24,654,991	19,295,700	25,944,281	21,190,700	27,979,281	19,295,700	25,944,281	21,190,700	27,979,281
44,143,317	40,213,317	0.8	20,106,658	20,106,658	22,001,658	22,141,658	14,269,036	25,944,281	16,164,036	27,979,281	14,269,036	25,944,281	16,164,036	27,979,281
39,116,652	35,186,652	0.7	17,593,326	17,593,326	19,488,326	19,628,326	9,242,371	25,944,281	11,137,371	27,979,281	9,242,371	25,944,281	11,137,371	27,979,281
34,089,988	30,159,988	0.6	15,079,994	15,079,994	16,974,994	17,114,994	4,215,707	25,944,281	6,110,707	27,979,281	4,215,707	25,944,281	6,110,707	27,979,281
29,063,323	25,133,323	0.5	12,566,662	12,566,662	14,461,662	14,601,662	3,997,163	21,136,160	5,892,163	23,171,160	0	25,133,323	1,895,000	27,168,323
24,036,658	20,106,658	0.4	10,053,329	10,053,329	11,948,329	12,088,329	3,997,163	16,109,495	5,892,163	18,144,495	0	20,106,658	1,895,000	22,141,658
19,009,994	15,079,994	0.3	7,539,997	7,539,997	9,434,997	9,574,997	3,997,163	11,082,831	5,892,163	13,117,831	0	15,079,994	1,895,000	17,114,994
13,983,329	10,053,329	0.2	5,026,665	5,026,665	6,921,665	7,061,665	2,582,465	7,470,864	4,477,465	9,505,864	0	10,053,329	1,895,000	12,088,329
9,265,416	5,026,665	0.1	2,513,332	2,513,332	4,408,332	4,548,332					0	5,026,665	1,895,000	7,061,665
3,930,000	0	0	0	0	1,895,000	2,035,000	0	0	1,895,000	2,035,000	0	0	1,895,000	2,035,000



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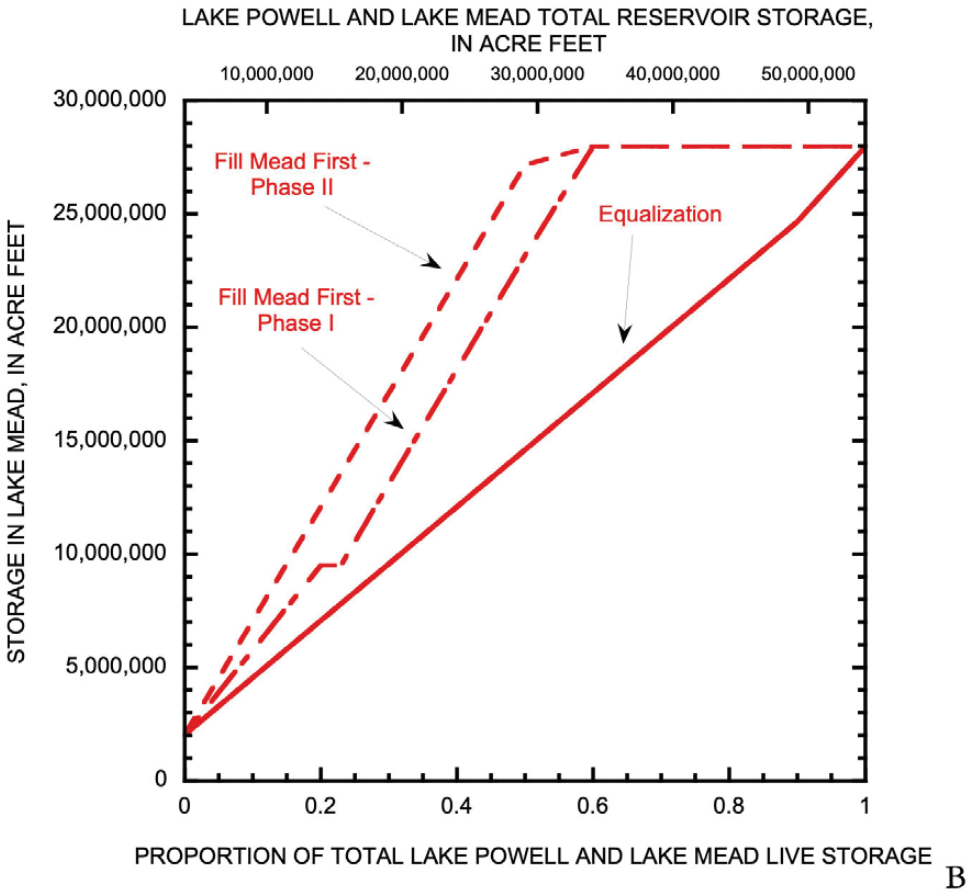
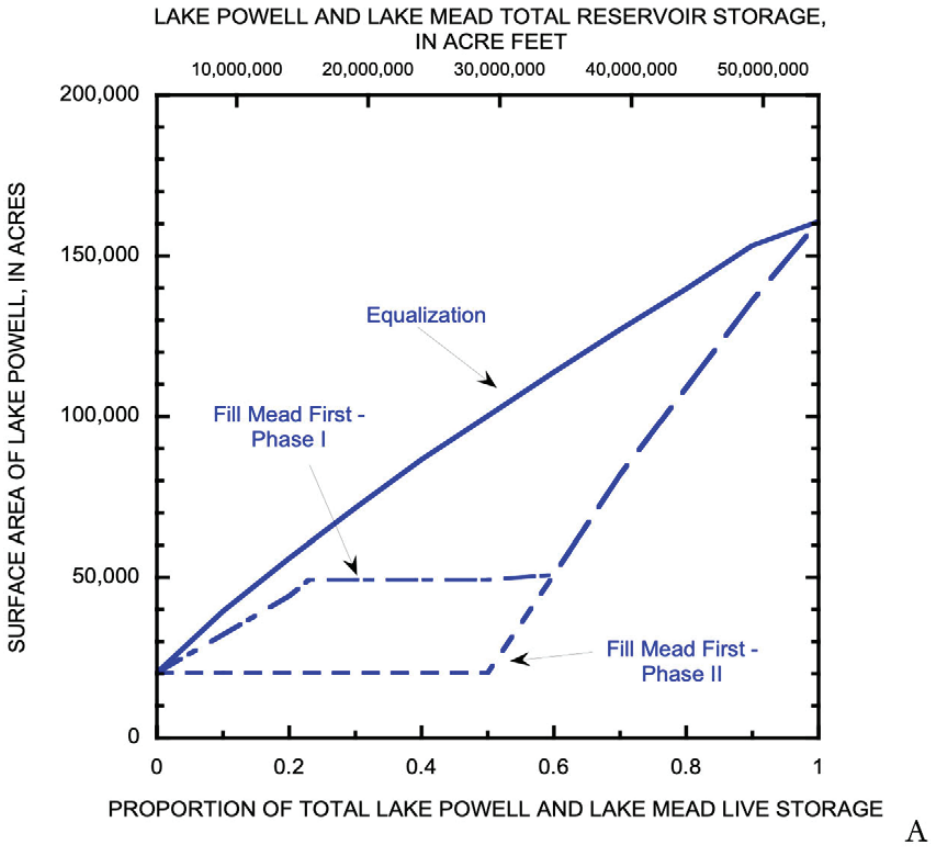


B

Figure 13. Graphs showing our simplifying assumptions about how much storage is accommodated in Lake Powell (A) and in Lake Mead (B) under the present strategy of equalizing active storage contents, as well as our assumptions about how storage would be allocated between Phase I of Fill Mead First and Phase II of Fill Mead First. The horizontal axis is the total storage in both reservoirs (see Table 3 and text for explanation), also represented as the proportion of total active storage.



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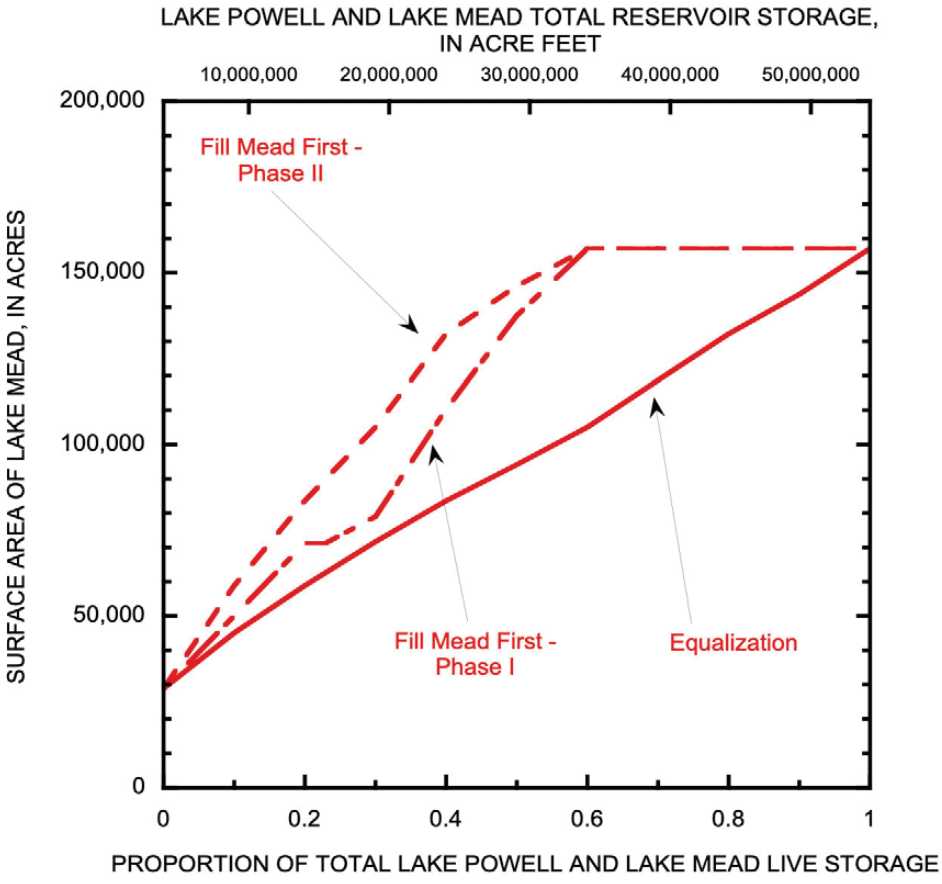


Figure 14. Graphs showing the surface area of Lake Powell (A) and Lake Mead (B) for the present equalization strategy and for the two phases of FMF. These data are based on the storage-to-surface area relations shown in Figure 7 multiplied by the scenarios shown in Figure 10.

The present equalization rule inevitably results in the surface areas of each reservoir being approximately the same regardless of whether the reservoirs are relatively empty or relatively full (Fig. 14). Implementation of FMF would decrease the total surface area of the two reservoirs, because the surface area of Lake Powell would be held constant at a low elevation and the proportional increases in the surface area of Lake Mead would be less that the proportional increases in surface area that occur when storage is equally divided (Fig. 15). When Lake Mead is full and Lake Powell is at minimum power pool elevation (i.e., FMF Phase I, total reservoir contents are ~60% of capacity), Lake Powell is ~55% smaller and Lake Mead is ~50% larger than when the same active storage is equally distributed between the two reservoirs. When Lake Mead is full and Lake Powell is at dead pool elevation (i.e., FMF Phase II, total reservoir contents are ~50% of capacity), Lake Mead's surface area is ~55% larger and Lake Powell's surface area is ~80% smaller than if the same active storage is divided equally between the two reservoirs. When the active storage is 50% of the capacity of the two reservoirs such as has been the case during the last few years, the total surface area of both reservoirs would be 4% less if the FMF – Phase I plan was adopted and would be 14% less if the FMF – Phase II plan was adopted (Fig. 15). When the active storage is 30% of capacity (a relatively "empty" reservoir system that has not ever occurred), the total reservoir surface area is approximately 10% less under FMF – Phase I scenario and 12% less under the FMF – Phase II scenario – than under the present equalization plan.

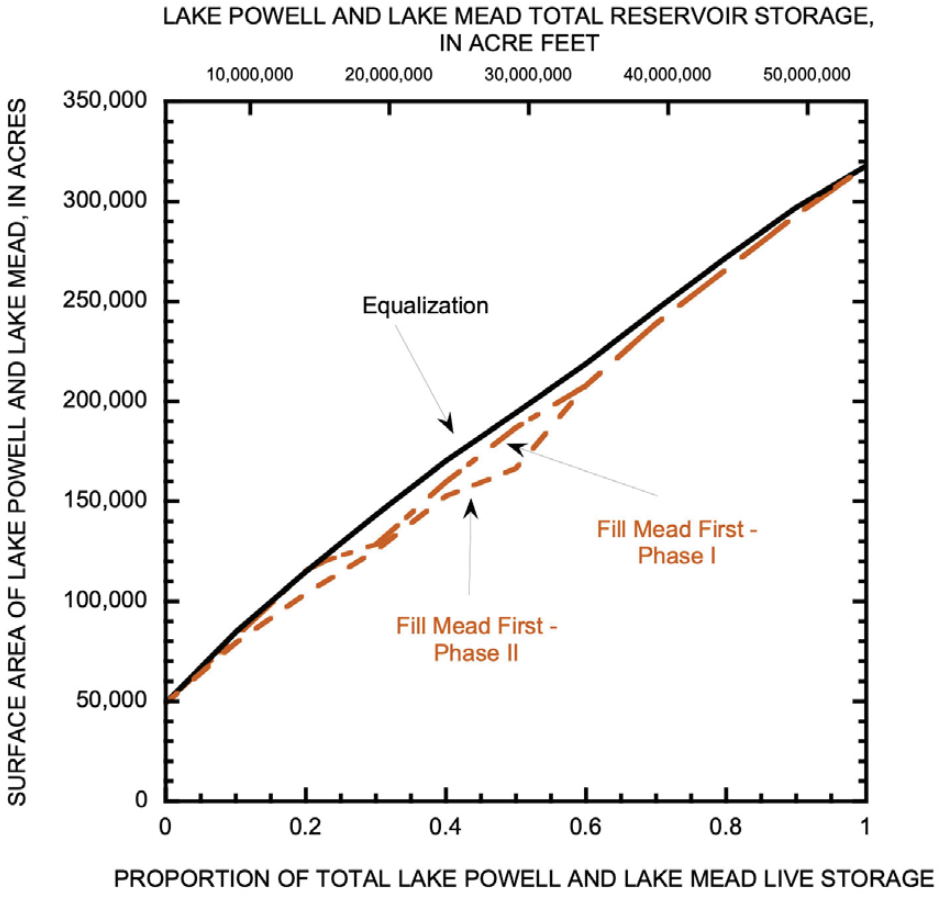
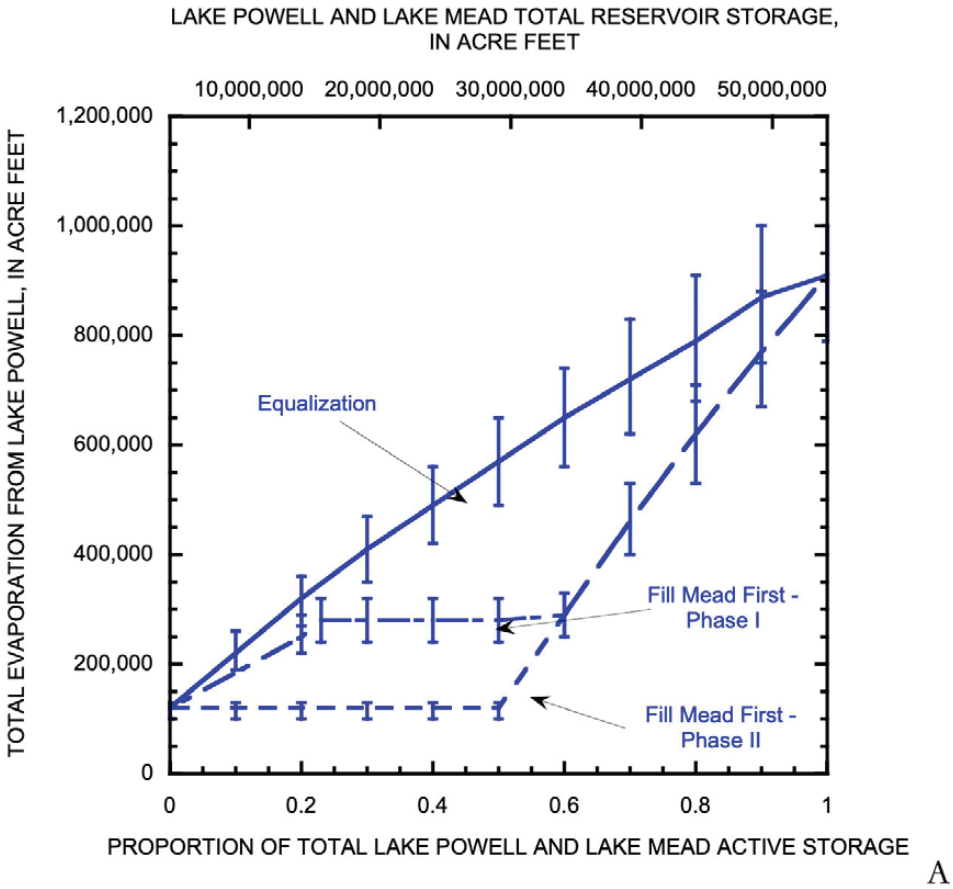


Figure 15. Graph showing the total reservoir surface area of Lake Powell and Lake Mead (B) for the present equalization strategy and for the two phases of FMF under different total system reservoir storage contents.



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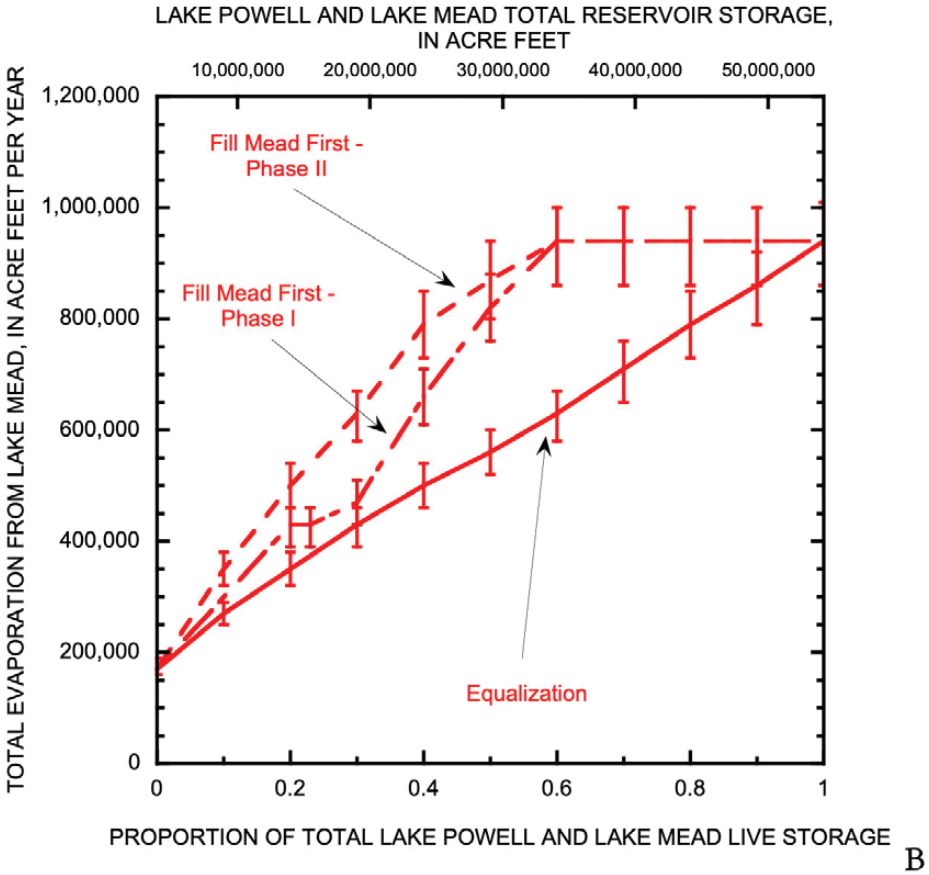


B

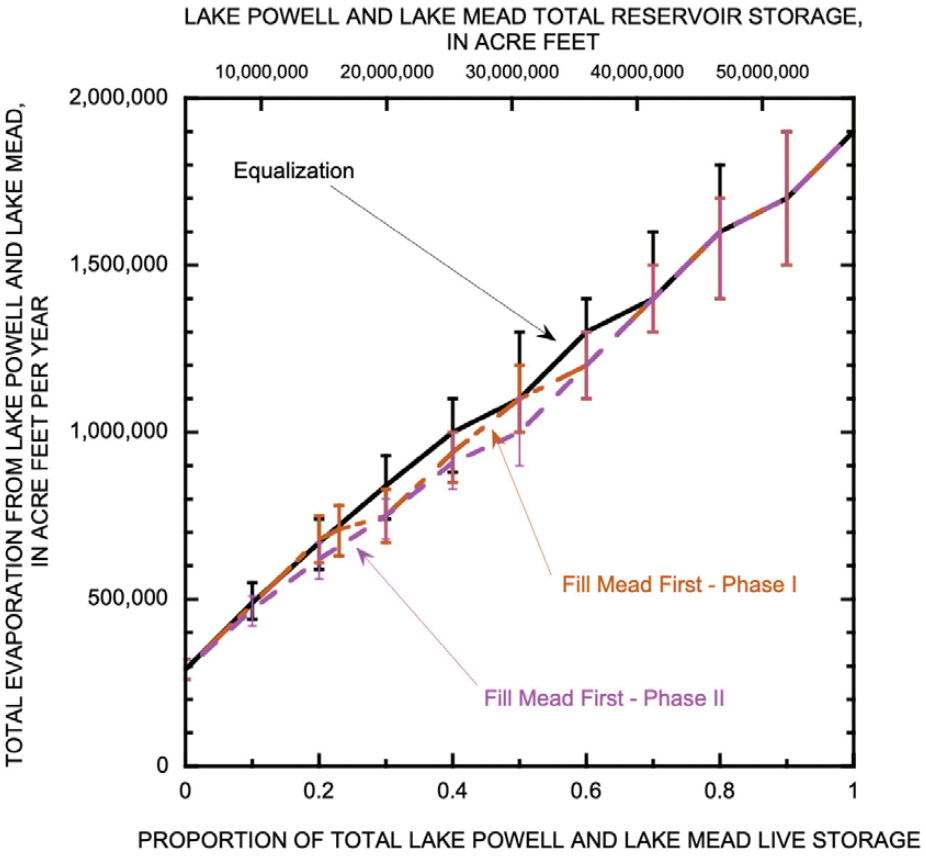
Figure 16. Graphs showing the estimated evaporation from Lake Powell (A) and Lake Mead (B) for different amounts of total reservoir storage and under different management scenarios. Error bars represent the range of estimated evaporation, as explained in the text.

Table 4. Estimated evaporation rates from Lake Powell and Lake Mead under different management scenarios. Uncertainty reflects differences in estimated evaporation rates, as explained in the text.

			Equalization		Fill Mead First – Phase I		Fill Mead First – Phase II	
Total storage in Lake Powell and Lake Mead, in acre feet	Total active storage, in acre feet	proportion of total system live storage	Lake Powell	Lake Mead	Lake Powell	Lake Mead	Lake Powell	Lake Mead
54,196,646	50,266,646	1	910,000 (±105,000)	940,000 (±75,000)	910,000 (±105,000)	940,000 (±70,000)	910,000 (±105,000)	940,000 (±70,000)
49,169,981	45,239,981	0.9	870,000 (±125,000)	860,000 (±65,000)	770,000 (±105,000)	940,000 (±70,000)	770,000 (±105,000)	940,000 (±70,000)
44,143,317	40,213,317	0.8	790,000 (±115,000)	790,000 (±60,000)	620,000 (±90,000)	940,000 (±70,000)	620,000 (±90,000)	940,000 (±70,000)
39,116,652	35,186,652	0.7	720,000 (±105,000)	710,000 (±55,000)	460,000 (±65,000)	940,000 (±70,000)	460,000 (±65,000)	940,000 (±70,000)
34,089,988	30,159,988	0.6	650,000 (±90,000)	630,000 (±45,000)	290,000 (±40,000)	940,000 (±70,000)	290,000 (±40,000)	940,000 (±70,000)
29,063,323	25,133,323	0.5	570,000 (±80,000)	560,000 (±40,000)	280,000 (±40,000)	820,000 (±60,000)	120,000 (±15,000)	870,000 (±70,000)
24,036,658	20,106,658	0.4	490,000 (±70,000)	500,000 (±40,000)	280,000 (±40,000)	660,000 (±50,000)	120,000 (±15,000)	790,000 (±60,000)
19,009,994	15,079,994	0.3	410,000 (±60,000)	430,000 (±35,000)	280,000 (±40,000)	470,000 (±40,000)	120,000 (±15,000)	630,000 (±45,000)
13,983,329	10,053,329	0.2	320,000 (±45,000)	350,000 (±30,000)	250,000 (±35,000)	430,000 (±35,000)	120,000 (±15,000)	500,000 (±40,000)
8,956,665	5,026,665	0.1	220,000 (±35,000)	270,000 (±20,000)			120,000 (±15,000)	350,000 (±30,000)
3,930,000	0	0	120,000 (±15,000)	170,000 (±15,000)	120,000 (±15,000)	170,000 (±15,000)	120,000 (±15,000)	170,000 (±15,000)

If FMF was implemented, the evaporation from Lake Powell would be less than under the equalization rule, and the evaporation from Lake Mead would be more. Under the present strategy of equalizing reservoir active storage and when total reservoir storage is similar or much less than today's conditions, evaporation from Lake Powell and from Lake Mead is approximately the same (Table 4). When the water-system active storage is 50% of capacity (i.e., active storage in each reservoir is 13.3 million af), evaporation is 0.57 million af/yr. (range 0.49-0.65 million af/yr) and 0.56 million af/yr (range 0.52-0.60 million af/yr) from Lake Powell and Lake Mead, respectively. Evaporation is 0.41 million af/yr (range 0.35-0.47 million af/yr) and 0.43 af/yr (range 0.39-0.46 million af/yr), respectively, when the water-system live storage is 30% of capacity and the active storage in each reservoir is 5.3 million af (Fig. 16).

Under Phase I or Phase II of FMF, it cannot be demonstrated that the total evaporation from the two reservoirs would be significantly different from the estimated losses under the equalization rule. The estimated total gross evaporation would be less if the FMF plan were implemented, but the uncertainty in these estimates is large (Fig. 17, Table 5). Reduced storage and reduced evaporation in Lake Powell is approximately matched by increased evaporation from Lake Mead. Total evaporation from Lake Powell is estimated to be ~0.28 million af/yr (range 0.24-0.32 million af/yr) when the reservoir is at minimum power pool and would be ~0.12 million af/yr (range 0.10-0.13 million af/yr) when the reservoir is at dead pool. However, evaporation from Lake Mead is estimated to be 0.82 million af/yr (range 0.76-0.88 million af/yr) when the two reservoirs store 50% of their capacity and Lake Mead's active storage is 21.1 million af). When the two reservoirs store 30% of their capacity (i.e., FMF Phase I; Lake Mead has 11.1 million af of active storage and Lake Powell is at minimum power pool elevation), evaporation losses from Lake Mead are estimated to be 0.47 million af/yr (range 0.43-0.51 million af/yr). Thus, if FMF Phase I was implemented and the total amount of water stored in the two reservoirs was 50% of total capacity, total evaporation losses are estimated to be ~1.1 million af/yr (range 1.0-1.2 million af/yr); this is the same estimated total evaporation losses as under the present equalization rule. If FMF Phase I was implemented and the total amount of water stored in the two reservoirs was 30% of total capacity, total evaporation losses are estimated to be ~0.75 million af/yr (range 0.67-0.83 million af/yr); evaporation losses under the present equalization rule and at the same magnitude of total reservoir storage is estimated to be ~0.84 million af/yr (range 0.74-0.93 million af/yr). If Phase II was implemented and the total reservoir storage was ~50% of capacity, Lake Powell would be at dead pool and Lake Mead would be nearly full. Under this scenario, total reservoir evaporation would be ~1.0 million af/yr (range 0.9-1.1 million af/yr), and this estimate overlaps the uncertainty range for storing the same amount of water under the present equalization scheme (~1.1 million af/yr; range 1.0-1.3 million af/yr). Similar overlaps in estimates exist at all other reservoir storage conditions.



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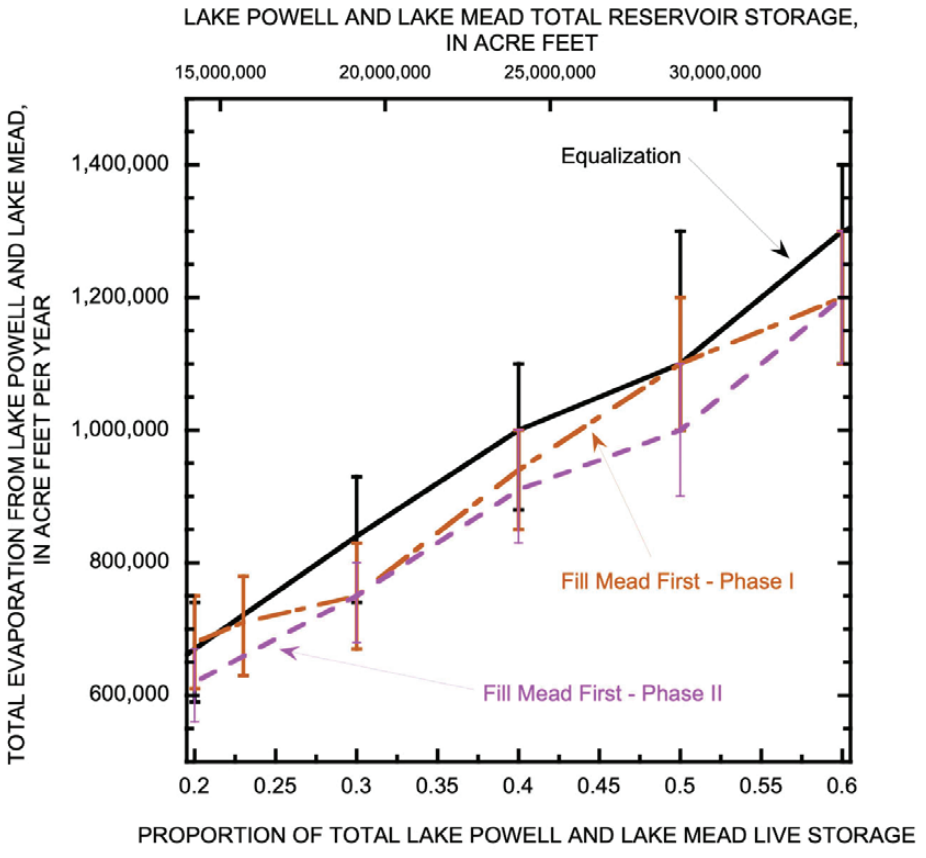


B

Figure 17. Graphs showing total annual evaporation as a function of total storage of water in Lake Powell and Lake Mead. Error bars represent the range of uncertainty as explained in the text. A is the full range of values of reservoir storage, and B is an inner range that extends from very little active storage (0.2 times the total active storage) to storage conditions similar to those that exist today (0.6 times the total active storage).

Table 5. Estimated total system evaporation under different management scenarios. Uncertainty reflects differences in estimated evaporation rates, as explained in the text.

			Present strategy -- Equalization of reservoir contents, in acre feet			Fill Mead First - Phase I, in acre feet			Fill Mead First - Phase II, in acre feet		
Total storage in Lake Powell and Lake Mead, in acre feet	Total active storage, in acre feet	proportion of total system live storage	high estimate	middle estimate	low estimate	high estimate	middle estimate	low estimate	high estimate	middle estimate	low estimate
54,196,646	50,266,646	1	2,000,000	1,900,000	1,700,000	2,000,000	1,900,000	1,700,000	2,000,000	1,900,000	1,700,000
49,169,981	45,239,981	0.9	1,900,000	1,700,000	1,500,000	1,900,000	1,700,000	1,500,000	1,900,000	1,700,000	1,500,000
44,143,317	40,213,317	0.8	1,800,000	1,600,000	1,400,000	1,700,000	1,600,000	1,400,000	1,700,000	1,600,000	1,400,000
39,116,652	35,186,652	0.7	1,600,000	1,400,000	1,300,000	1,500,000	1,400,000	1,300,000	1,500,000	1,400,000	1,300,000
34,089,988	30,159,988	0.6	1,400,000	1,300,000	1,100,000	1,300,000	1,200,000	1,100,000	1,300,000	1,200,000	1,100,000
29,063,323	25,133,323	0.5	1,300,000	1,100,000	1,000,000	1,200,000	1,100,000	1,000,000	1,100,000	1,000,000	900,000
24,036,658	20,106,658	0.4	1,100,000	1,000,000	880,000	1,000,000	940,000	850,000	1,000,000	910,000	830,000
19,009,994	15,079,994	0.3	930,000	840,000	740,000	830,000	750,000	670,000	800,000	750,000	680,000
13,983,329	10,053,329	0.2	740,000	670,000	590,000	750,000	680,000	610,000	670,000	620,000	560,000
8,956,665	5,026,665	0.1	550,000	490,000	440,000				510,000	470,000	420,000
3,930,000	0	0	320,000	290,000	260,000	320,000	290,000	260,000	320,000	290,000	260,000

4.5. Bank Storage and Seepage

Some amount of reservoir water inevitably moves into the surrounding bedrock and unconsolidated geologic formations when a reservoir initially fills. Jacoby et al. (1977) observed:

> [Ground-water][43] storage is a phenomena that occurs in every reservoir, lake, and stream in the world. In many cases the storage and its effects on a water body are negligible. In some cases, such as Lake Powell, the [ground-water] storage may be a significant portion of the total storage of the reservoir. In the case of [Lake Powell], knowledge of the distribution and availability of the stored water is essential in order to determine whether it is real storage, a water loss, or what combination of the two. If the bank storage is readily available for return to the reservoir as the water level recedes, the storage can be regarded as part of the overall reservoir storage. If it will <u>not</u> return to the reservoir readily, it must be regarded as a water loss.

At issue in the evaluation of the efficacy of the FMF proposal is whether ground-water storage is $G_{storage:short}$ or is the quantity $(G_{storage:long} + G_{seepage})$. Meyers (2013a) argued that most of the ground-water storage around Lake Powell is $G_{seepage}$, and Reclamation (Ryan, 1993) considers all ground-water storage to be $G_{storage:short}$ for purposes of CRSS modeling. Here, we show that $G_{seepage}$ is small, but $(G_{storage:long} + G_{storage:short})$ may be large.

Jacoby et al. (1977) illustrated how ground-water storage is changed by a reservoir (Fig. 18). Movement of water from the reservoir into the surrounding earth materials occurs so long as the elevation of the reservoir is higher than the potentiometric surface of the surrounding aquifer. Over time, water moving from the reservoir saturates the bedrock, and bank storage increases from polygon ABC to polygon DBC (Fig. 18). Movement ceases only when the potentiometric surface of the surrounding ground-water system is equal or higher than the elevation of water in the reservoir, and bank storage saturates all of polygon EBC. The rate of movement of reservoir water into the surrounding bedrock slows with time, because there is an increasing amount of bedrock through which the water must pass.

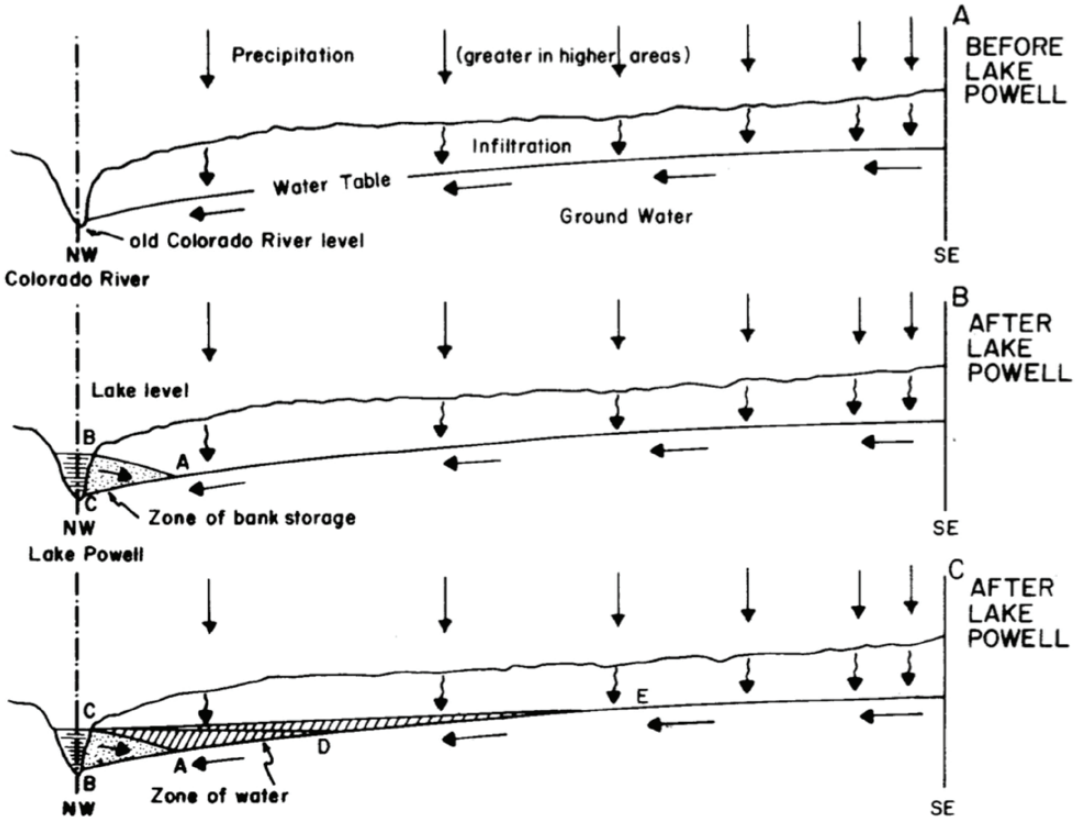


Figure 18. Generalized cross section showing how the distribution of bank storage was expected to change at Lake Powell (from Jacoby et al., 1977, fig. 20). See text for explanation.

Field measurements and numerical modeling can aid in estimating how much water can be accommodated in polygon EBC and how long that process will take. Long-term bank storage occurs when water in polygon EBC does not readily drain back into Lake Powell during periods of declining reservoir level, and bank seepage occurs where the elevation of the reservoir (point C in fig. 18) is higher than the potentiometric surface of the regional ground-water system and ground-water flow reverses at a regional scale. The water that is stored at elevations below that of dead pool is lost until the reservoir is fully drained.

The significance of movement of reservoir water into the surrounding ground-water system was recognized early in the filling of Lake Mead. Harbeck et al. (1958) observed, "Moreover, it was realized that … ground-water storage in the voids in the gravel, sand, and other rock material that underlie the reservoir … was of considerable magnitude." Langbein (1960)[44] estimated ground-water storage based on a water budget and found that "the annual change in gross storage averages about 12 percent more than the change in reservoir contents." He estimated that "water storage beneath the reservoir sides and bottom when the lake is filled to capacity is therefore of the order of 3,300,000 acre-feet" (Fig. 19), and this is the amount of water he estimated had moved into the surrounding ground-water system between 1935 and fall 1941 when Lake Mead filled for the first time. Langbein (1960) thought that all reservoir water that moved into the surrounding bedrock would return slowly to the reservoir during times when the reservoir elevation declined and should be considered $G_{storage:short}$.

The ground-water storage is not available during short-period changes in water level. It takes time for the water to permeate and drain the sediments containing this storage, and only a small proportion is available during the usual seasonal change in reservoir contents … preliminary studies indicate that bank storage of the extent indicated is available only for year-to-year changes in reservoir contents.

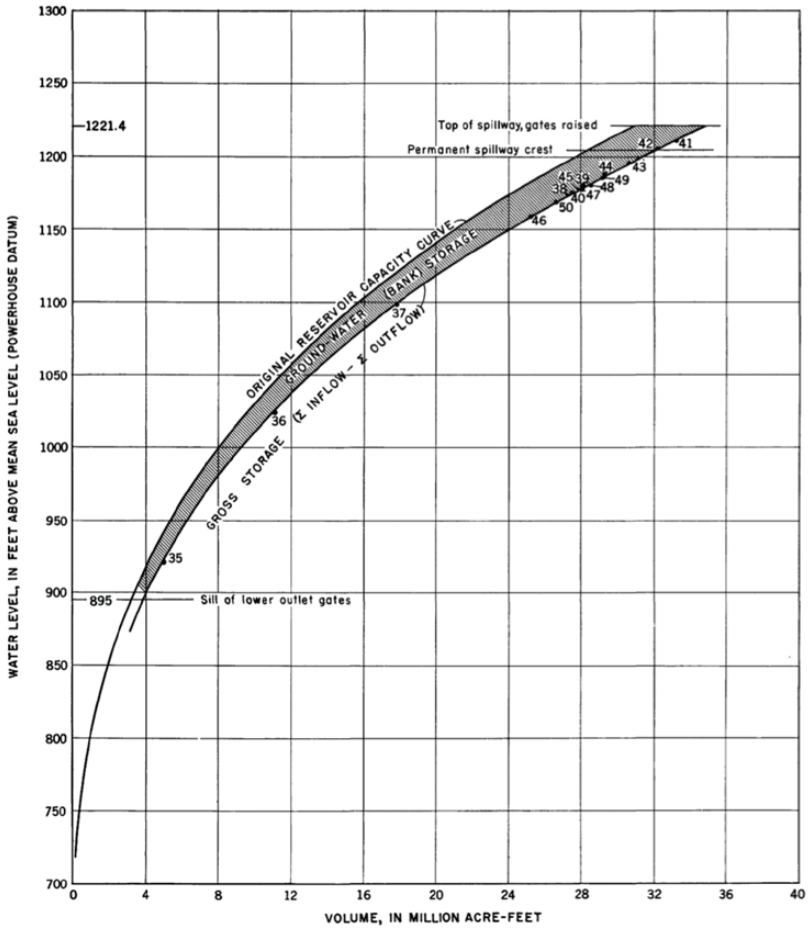


Figure 19. Graph showing capacity curve of Lake Mead and the total estimated storage capacity that includes bank storage, as estimated by Langbein (1960, fig. 21).

Blanchard (1986)[45] and Thomas (1986)[46] showed that the general direction of regional ground-water flow in southern Utah and northern Arizona is towards the Colorado River and Lake Powell (Figs. 20 and 21). The regional ground-water flow patterns were estimated from measurements of water levels in wells, the locations of springs, and the topography of the Navajo sandstone. Ground water generally moves southward from the Utah High Plateaus, Kaiparowits Plateau, and East Kaibab Monocline towards the Colorado River; ground water presumably also moves northward from Cedar Mesa, the Abajo Mountains, and Navajo Mountain to the canyons of the San Juan and Colorado Rivers, although no studies have directly measured flow patterns to the south of the reservoir. The elevations of the northern recharge areas are much higher than the maximum elevation of Lake Powell, making it impossible for water flowing from Lake Powell to reverse the regional ground-water flow pattern to the north. Thus, ground-water storage around Lake Powell is unlikely to be bank seepage, except in the vicinity of Glen Canyon Dam, as described below. Thomas (1986) observed:

> *Since Lake Powell came into existence, the general direction of ground-water movement has not changed. Water from Lake Powell is recharging the Navajo sandstone near the lake, but the regional flow system is still moving toward the lake. The major changes to the system are within about 20 miles of the lake shoreline. In this area, the water-level gradient toward the lake has flattened as water levels near the lake rise in response to recharge from the lake … Since the filling of Lake Powell, water in the Navajo sandstone that originally discharged to the Colorado River is now either going into storage, discharging to springs or streams near Lake Powell, discharging to the lake, or discharging to the Colorado River downstream from Glen Canyon Dam. The relative amounts of this pre-lake discharge that goes to these different areas cannot be estimated.*

Myers (2013a) pointed out that, "Because the sandstone dips to the north, water in the banks to the north may have barriers to overcome to return to the reservoir or river system and some may flow past a point where geology prevents its return … [but] … Neither simulations nor observations suggest a ground-water divide has or will form to prevent water from returning to the reservoir."

Significant amounts of reservoir water have moved into the earth materials that immediately surround Lake Powell. The water level in a well ~1 mi from the reservoir near Wahweap rose 395 ft between 1963 and 1983 as the reservoir filled. Water levels in wells approximately 5 mi away from Lake Powell near Big Water, UT, progressively rose after the construction of Glen Canyon Dam, also indicating cumulative additions into ground-water storage. Blanchard (1986) observed:

> *… the ground-water system within a few miles of the lakeshore is not in equilibrium … water presently is being diverted into storage in the form of [ground-water] storage along the lakeshore. The water level in well (D-38-11)5dca-1, at Bullfrog Marina [that is less than 1 mile from the reservoir], is about 50 feet below the normal surface altitude of the reservoir, and the water level in well (D-38-11)29cda-1, at Halls Crossing Marina [that is also less than 1 mile from the reservoir], is about 150 feet below the normal surface altitude of the reservoir. Both water levels indicate that ground-water movement is from the reservoir into the canyon walls …*

The water level in the well at Bullfrog Marina rose 52 ft between 1964 and 1984; water level at the well at Halls Crossing Marina rose approximately 220 ft between 1966 and 1984 (Blanchard, 1986).

Because there so little development in the Lake Powell region, one cannot rely solely on measurements of water level in wells to evaluate the characteristics of ground-water flow. Thomas (1986) developed a 2-dimensional, finite difference numerical model and predicted ground-water flow in a 600-mi^2 study area near Wahweap based on a range of likely hydro-geologic characteristics of the Navajo sandstone. The model is only a crude estimate of ground-water flow characteristics, was only calibrated to

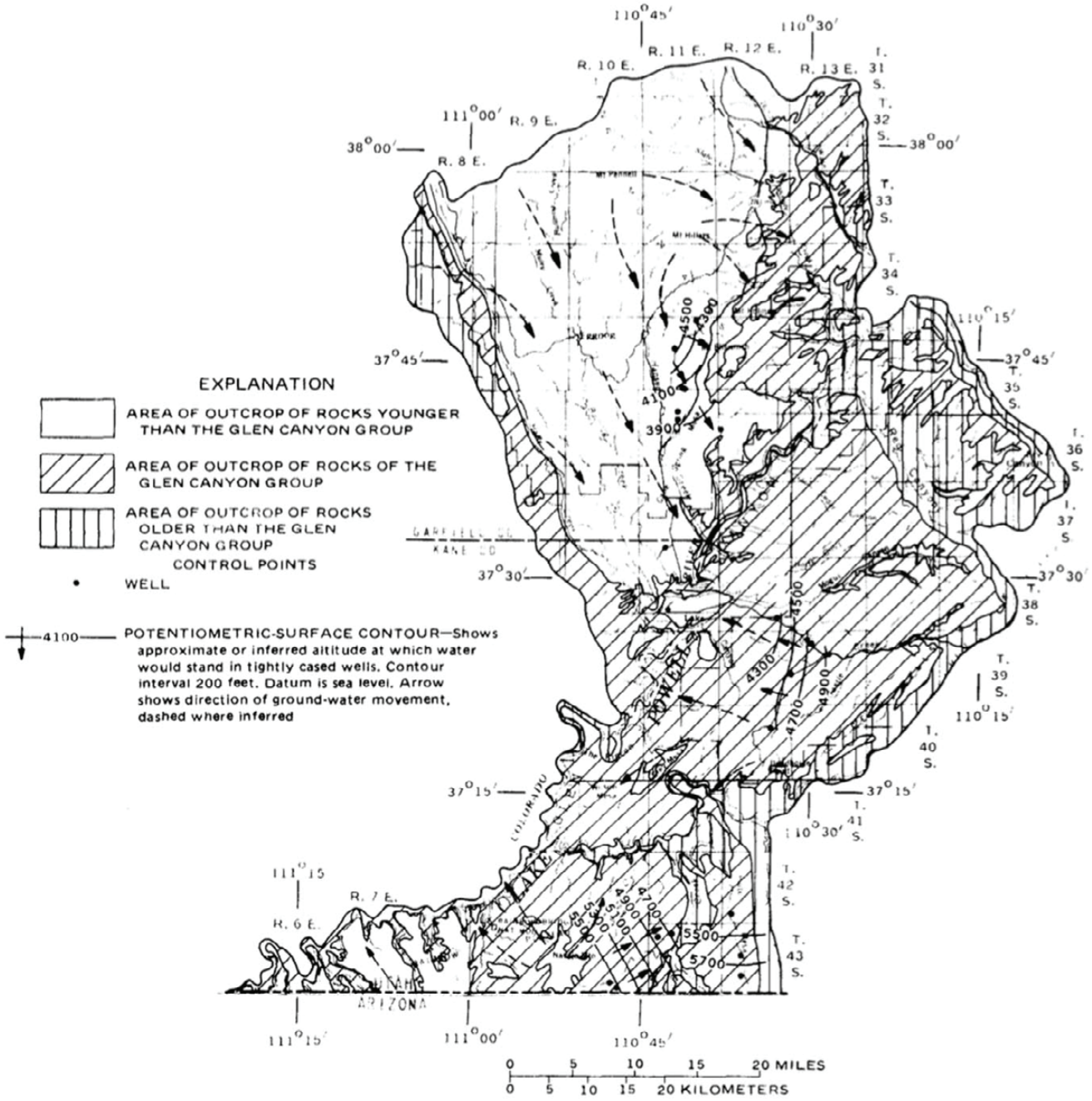


Figure 20. Map showing approximate potentiometric surface and general direction of ground-water flow in the Navajo sandstone (Blanchard, 1986, fig. 10).

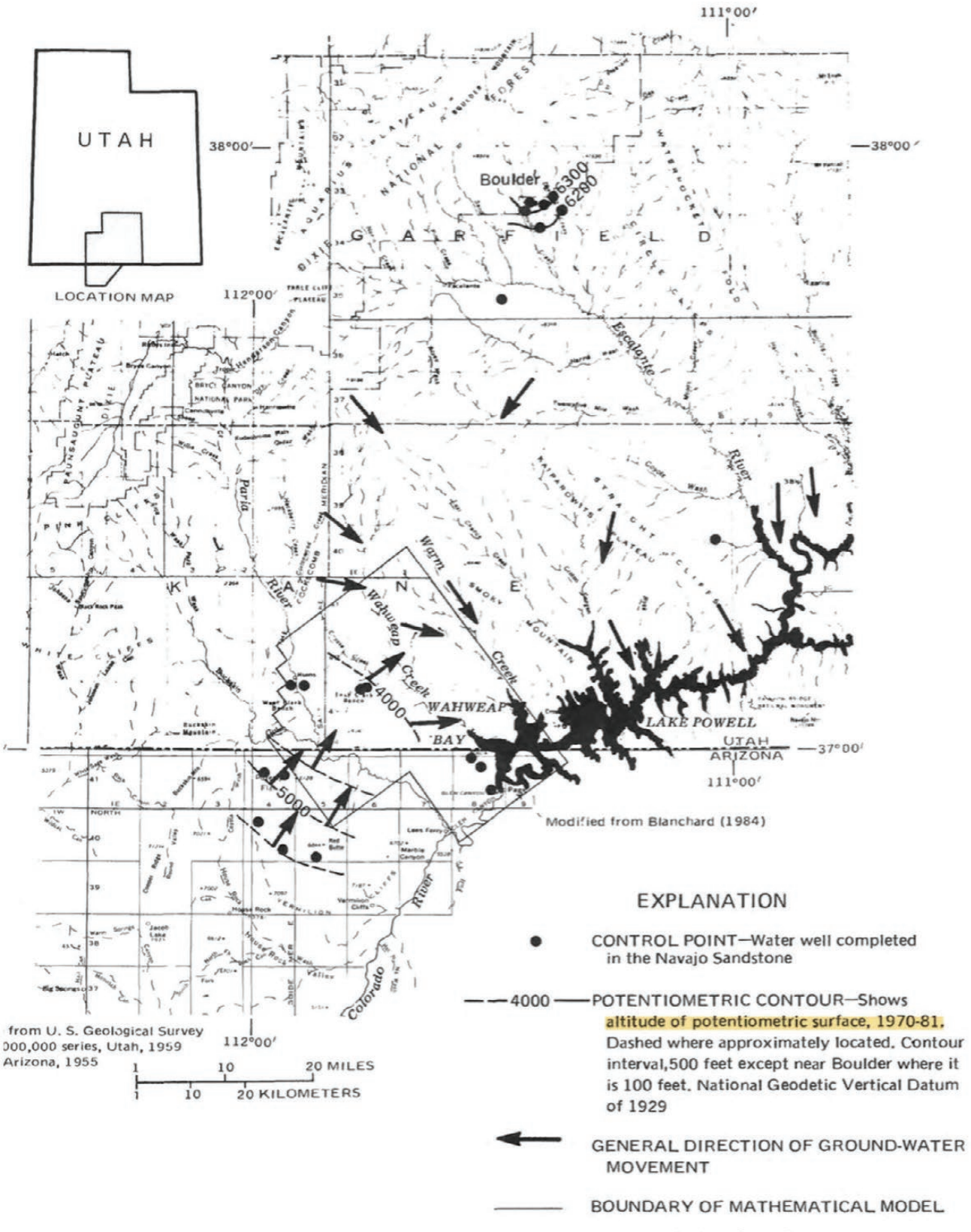


Figure 21. Map showing approximate potentiometric surface and general direction of movement of water in the Navajo sandstone (Thomas, 1986, fig. 6).

the few wells that existed in the region in the early 1980s, and represents state-of-the science ground-water modeling typical of the early 1980s. Nevertheless, the model provides a reasonable estimate of the large-scale changes in ground-water flow caused by the filling of Lake Powell (personal communication, S. A. Leake, hydrologist-retired, Arizona Water Science Center, U.S. Geological Survey). The model results indicate that ground-water flow paths were significantly changed very near the dam where some ground water now flows around the dam and re-enters the Colorado River upstream from Lees Ferry; elsewhere, changes in flow directions have been insignificant (Fig. 22).

Thomas (1986) estimated that the wetting front of newly stored ground water propagated approximately 20 mi from Lake Powell during the first 20 years of the reservoir's existence. He estimated that the potentiometric surface was increased by approximately 25 ft at a distance of approximately 15 mi west from the reservoir (Fig. 23). This increase in water content represents the gradual filling of polygon DBC in figure 18. Thomas (1986) observed, "… the response of the aquifer to the filling of Lake Powell can be visualized as a front of water moving slowly through the sandstone" (Thomas, 1986).

Using a water budget, Jacoby et al. (1977) estimated that 8.4 maf of reservoir water entered the regional ground-water system between July 1, 1963, and January 1, 1976, at an average rate of approximately 0.61 million af/year. The rate of ground-water storage estimated by Jacoby et al. (1977) declined as a proportion of the change in total reservoir storage, based on comparison of the rates during 3 periods when reservoir storage progressively increased (Table 6).

Thomas (1986) estimated that ground-water storage during the first 20 years of reservoir filling was between 0.0070 and 0.030 million af per mile of reservoir shoreline, which is an annual loss rate of 0.00035 to 0.0015 million af/shoreline mi/yr. He noted that "about 25,000 acre-feet per mile [an annual rate of 1,200 af/mi/yr] … is probably the most reasonable single value." Thus, he estimated that the total volume of water that moved into ground-water storage between 1963 and 1983 was between 2.1 and 9.0 million af. Thomas (1986) considered the best estimate of this value to be approximately 7.5 million af, which is an annual average rate of ground-water storage of 0.37 million af/yr. These annual rates are less than those estimated by Jacoby et al. (1977) and support the conclusion that the rate of ground-water storage decreased with time. Clearly, there is significant uncertainty in these estimate, because Thomas' (1986) estimates are based on a numerical model of ground-water flow of a 600-mi^2 study area and extrapolation to the entire shoreline of Lake Powell.

Using a water budget approach, Myers (2013a) estimated that between 9.6 and 15.2 million af of water had moved from the reservoir into ground-water storage between 1963 and 2009. He estimated that 12.0 million af of this storage occurred prior to 1983 and that storage or drainage of ground water fluctuated thereafter. Myers' (2013a) estimate of ground-water storage between 1963 and 1983 was approximately 60% greater than that estimated by Thomas (1986). Myers (2013a) found that the rate of ground-water storage had greatly decreased after 1983 (Fig. 8), and that the decreasing rate was related to the changes in reservoir storage in Lake Powell. Nevertheless, Myers' (2103a) findings are consistent with Thomas' (1986) finding that the rate of ground-water storage will decrease with time. Despite this large difference in estimates of cumulative ground-water storage, neither Jacoby et al. (1977), Blanchard (1986), Thomas (1986), or Myers (2013a) disagree on the existence of long-term bank storage ($\overline{G_{storage:long}}$). The observations and modeling results of Thomas (1986) and Blanchard (1986) do not indicate that $\overline{G_{seepage}}$ occurs anywhere except near Glen Canyon Dam. No studies have specifically evaluated the potential for long-term ground-water movement far away from Lake Powell, as speculated by Myers (2013a), or of evaporation of accumulating ground-water storage in topographically low areas near or south from the reservoir.

Thomas (1986) used his model to estimate how long it will take Lake Powell to fully saturate the surrounding bedrock such that equilibrium conditions exist; in other words, how

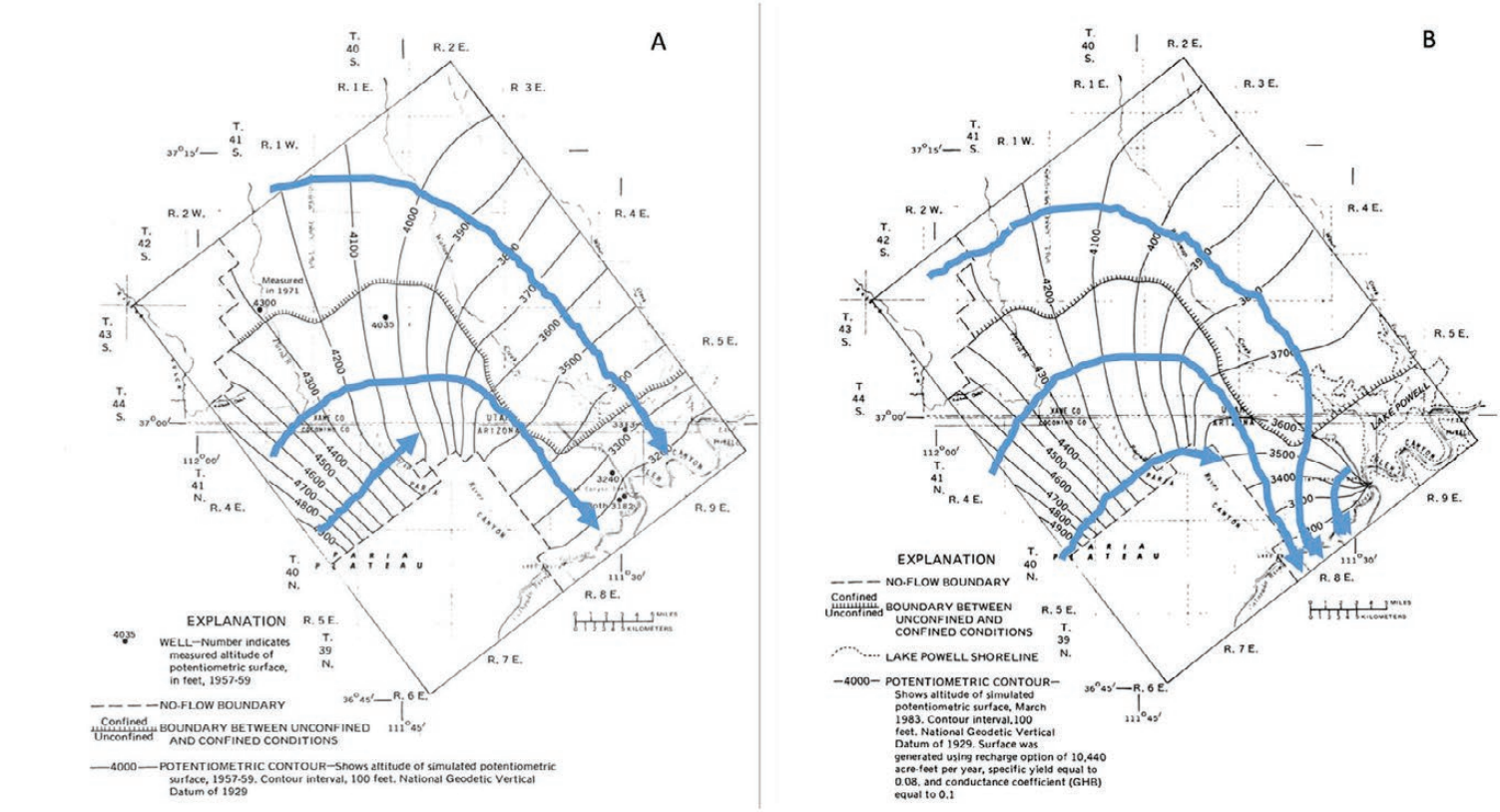


Figure 22. Maps showing estimated equilibrium potentiometric surface and ground-water flow paths (blue arrows) that existed (A) before construction of Glen Canyon Dam and (B) in March 1983. (Thomas, 1986, figures 10 and 13).

Table 6. Summary of various estimates of ground-water storage

Time Period	Change in reservoir storage, in million acre-feet per year[57]	Annual ground-water storage rate, in million acre-feet per year	Annual ground-water storage rate per unit shoreline distance, in million acre-feet per mile per year[58]	Ground-water storage as proportion of reservoir storage
July 1, 1963 – June 1, 1966[59]	2.1	0.85	0.0028	0.40
April 1, 1968 – July 1, 1971[59]	2.6	0.69	0.0023	0.27
April 1, 1973 – June 1, 1976[59]	2.9	0.68	0.0023	0.23
1963-1983[60]	1.1	0.37 (0.10-0.45)	0.0012 (0.00035-0.0015)	0.34 (0.09-0.41)
1963-1983[61]	1.1	(0.48-0.76)	(0.0016-0.0025)	(0.44-0.69)
1983-2033[60]		0.054 (0.015-0.065)	0.00018	
2033-2083[60]		0.032 (0.0012-0.0051)	0.00011	

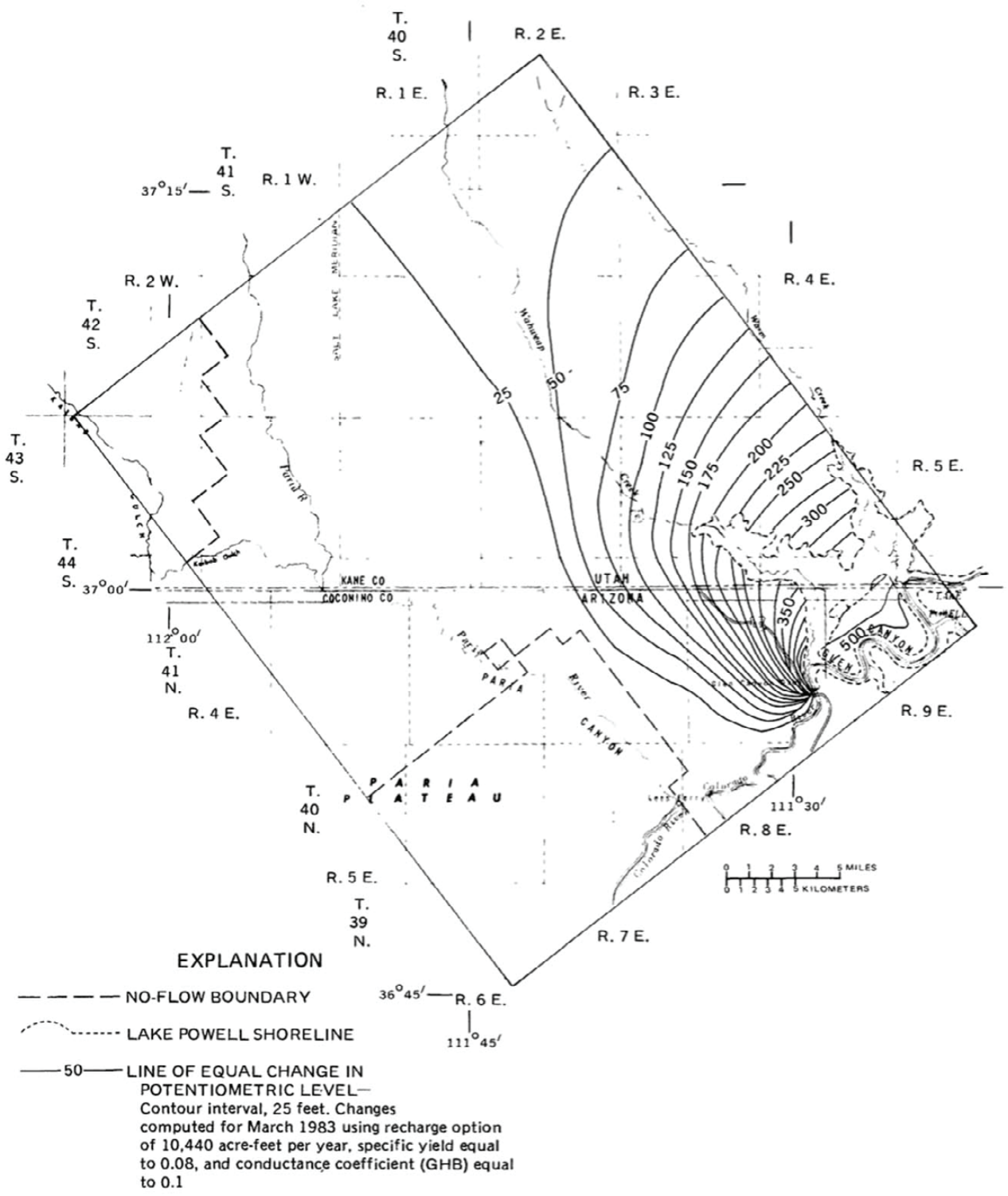


Figure 23. Map showing simulated increases in the elevation of the potentiometric surface of the Navajo sandstone aquifer that occurred between 1963 and 1983 (Thomas, 1986, Fig. 12).

long will it take to fully saturate polygon EBC in figure 18? Thomas (1986) assumed that Lake Powell would be maintained at an average elevation of 3680 ft, which is 21.3 million af of storage above dead pool (87% of total active storage) and 23.2 million af total storage. With the assumption that Lake Powell is maintained at a relatively full level, Thomas (1986) estimated that half of the total ground-water storage had accumulated by 1983, and that the other half would accumulate during a period of between 80 and 700 years; he considered a duration of 400 years to be the most reasonable estimate. Thomas (1986) estimated that 36% of the additional ground-water storage would move into the surrounding bedrock by about 2033 and that 57% would accumulate by about 2083. Extrapolation of Thomas' (1986) calculations suggest that ultimately approximately 15 million af[47] will move into the surrounding bedrock assuming that Lake Powell will be maintained mostly full. The total amount in ground-water storage will be less if Lake Powell is operated at lower elevations. Lake Powell has not been at 3680 ft since 2001, so Thomas' (1986) estimates probably overestimate the likely future ground-water storage.

During the inevitable periods when inflows to Lake Powell are less than outflows, some of the ground-water storage moves back to the reservoir. This water is the quantity $\overline{G_{storage:short}}$. Jacoby et al. (1977) observed, "When the water level drops there is appreciable return flow back into the reservoir. The actual proportion of returnable [ground-water] storage is difficult to estimate." Thomas (1986) observed that:

> *Water levels in wells within 1 mile of the lake shoreline indicate that the direction of ground-water movement near the lake reverses following the seasonal fluctuations of the lake level …… As lake levels decline after spring runoff, water stored in the Navajo sandstone discharges to the lake. This discharge … is indicated by the decline of water levels in wells close to the shoreline. The distance from the shoreline where this movement can no longer be observed is unknown.*

Jacoby et al. (1977) estimated that approximately 0.30 million af flowed back into the reservoir during a period of lowering in 1973, demonstrating that, "bank storage is indeed a storage phenomena. It is not water totally lost for future use, however the full evaluation of its recoverability may have to wait until the reservoir has been operating for several more years." Blanchard (1986) observed that "… a reversal of the normal ground-water gradient to Glen Canyon is present immediately along the shore of the lake." Myers (2013a) recognized that some proportion of ground-water storage is short-term bank storage, and he estimated that approximately 0.81 million af moved back into the reservoir during the reservoir decline between June 1989 and February 1995 and that approximately 2.0 million af was released from storage back into the reservoir during drawdown between 1998 and April 2008.

Short-term bank storage was also estimated at Lake Mead. Langbein (1960) estimated that approximately 0.91 million af returned to the reservoir during a 5-year period between September 1941 and September 1946 when Lake Mead declined by approximately 52 ft; this is 28% of the ground-water storage that had accumulated in the preceding 6 years. The ground-water storage area surrounding Lake Mead varies greatly in its spatial extent, depending on whether the surrounding area is bedrock or unconsolidated alluvium. Although there are no recent studies of ground-water movement in the Lake Mead area, the area affected by ground-water movement in and out of the reservoir has been defined as part of the definition of the Lower Colorado River accounting surface (Wiele et al., 2009)[48]. In some places, the area affected by changes in storage at Lake Mead is significant (Fig. 24), although elsewhere saturated bedrock only extends approximately 0.5 mile away from the reservoir (Laney and Bales, 1996)[49].

These data concerning ground-water storage are difficult to incorporate into water resource models, such as applied by Reclamation in the CRSS framework. Presently, Reclamation estimates that every increase or decrease in reservoir storage in Lake Powell includes an additional 8% that moves into the surrounding bedrock; on average, this is approximately 0.43

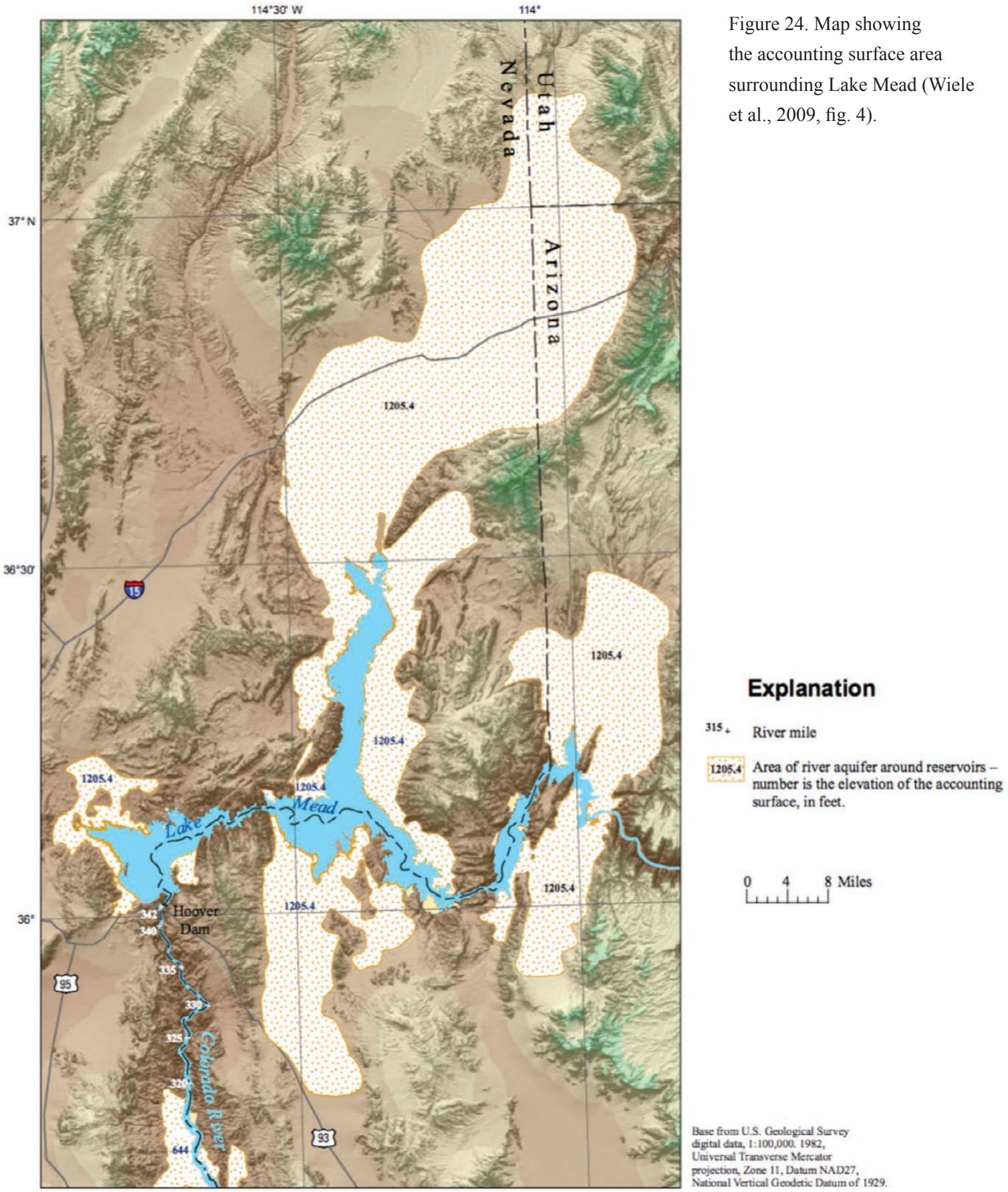


Figure 24. Map showing the accounting surface area surrounding Lake Mead (Wiele et al., 2009, fig. 4).

million af/mth or 5.2 million af/yr. Reclamation assumes that water flows back into Lake Powell during times when the reservoir elevation falls at the same rate. In other words, the agency assumes that the amount of water flowing back into the reservoir is the same proportion that entered the bedrock: 8% of the associated change in reservoir storage. For Lake Mead, the proportion is estimated to be 6.5% times the change in reservoir storage. For purposes of application within CRSS, Reclamation assumes that

$$G_{seepage} + G_{storage:long} = 0 \quad (8)$$

and that all bank storage fluctuations occur at a monthly time scale. Thus, Reclamation assumes that all water that enters the banks will return to the reservoir as soon as reservoir levels decrease. Myers (2013a) estimated that short-term bank storage fluctuations may be 12% of reservoir storage changes. All of these estimates suggest that $G_{storage:short}$ is less than $G_{storage}$, because the accumulated ground-water storage as a proportion of total increase in reservoir storage has never been estimated to be less than 23% (Table 6).

4.5.1. Conclusions

Every scientific study concerning the interactions of Lake Powell or Lake Mead with the surrounding ground-water system has concluded that:

- Ground water moves from the reservoir into the surrounding bedrock.
- The rate that ground water moves into the surrounding bedrock is relatively slow and declines with time. Most studies have estimated that equilibrium conditions are likely to take many centuries to develop, and no studies have predicted losses with widely fluctuating water-storage conditions in Lake Powell. A proportion of ground-water storage is better considered long-term bank storage and is not available to meet decadal-scale water supply needs;
- In the case of Lake Powell, changes in ground-water storage are likely to occur as far as 20 miles away from the reservoir;
- Lake Mead is much older than Lake Powell, and published studies indicate that the zone of saturated bedrock only occurs within approximately 1 mi of the reservoir but that the zone of saturated unconsolidated alluvium extends many 10s of miles away;
- There is no evidence of bank seepage losses from Lake Powell, except around the north side of Glen Canyon Dam. That water seeps back into the Colorado River upstream from Lees Ferry.
- No studies have described ground-water movement south from Lake Powell or around the south side of Glen Canyon Dam.

Every scientific study concerning the water balance of Lake Mead or Lake Powell has found that estimates of ground-water storage have been made based on sparse data. In 1986, Thomas (1986) recommended drilling additional observation wells more distant from Lake Powell. New numerical modeling strategies could be employed to predict ground-water flow patterns and to evaluate changes in long-term and short-term bank storage. Ground-water modeling predicts that the rate of accumulation of long-term bank storage will slow to 10% of the rate that occurred during the first 20 years when Lake Powell first filled.

Thus, there is very large uncertainty associated with estimating losses associated with ground-water storage. Thomas (1986) recommended that the uncertainty in predicting the long-term fate of reservoir water and the prediction of how much water would ultimately become ground-water storage could be resolved by establishing additional observation wells:

> *Additional field data are needed to develop a more accurate model of the interaction of water in the Navajo sandstone and in Lake Powell … the most important area is within 5 miles of the lake shoreline. [Existing observation wells within 1 mile of Lake Powell] … provide useful information on the near-shoreline response of water levels in the Navajo sandstone to lake fluctuations. The*

best locations for additional observation wells would be between 1 and 5 miles from the shoreline. ... Additional observations wells are needed from 5 to 30 miles from the lake shoreline to define the regional characteristics of the system.

Although a small proportion of ground-water storage returns to the reservoir relatively quickly when the reservoir is drained, the physics of ground-water flow demand that there will be a net movement of water into long-term bank storage that will occur during the next few centuries, assuming that Lake Powell is maintained 80% full. Thomas (1986) estimated that the average rate of increase in ground-water storage into the bedrock around Lake Powell between 1963 and 1983 had been 0.37 million af/yr (range 0.10 – 0.45 million af/yr). However, the water budget calculations of Jacoby et al. (1977) showed that this rate declined with time, and was 0.85 million af/yr between 1963 and 1966 when the reservoir first began to fill. Thomas (1986) estimated that the rate of movement of ground-water into the surrounding earth materials would be approximately 0.054 million af/yr between 1983 and 2033. This estimate of future losses into the surrounding ground-water system is approximately an order of magnitude less that of Myers (2013a) who suggested that Lake Powell had lost 0.60 million af/yr between 1963 and 1983, and that the reservoir would continue to lose water at a rate of ~0.3 million af/yr far into the future.

4.6. *Ungaged Tributary Inflow*

Uncertainty in equations (4) and (5) also arises because of the imprecision in measuring inputs to the reservoirs. The precipitation onto Lake Powell and Lake Mead is very small; additional rain gages might be established around the reservoirs, but it is unlikely that a more accurate estimate of reservoir rainfall would reduce uncertainty in the water budget or have significant management implications. On the other hand, there is approximately 20,000 mi^2 of watershed area whose runoff into Lake Powell is not measured[50]. Myers (2013a) offered a strategy for estimating this inflow. Although such an approach might be useful, the best approach is to reduce the area of ungaged flow by establishing new gaging stations closer to Lake Powell. In 2014, the USGS Utah Water Science Center (USGS/UWSC) and the Grand Canyon Monitoring and Research Center (USGS/GCMRC) established gages on the Colorado River downstream from Moab (gage 09185600, Colorado River at Potash, UT) and on the Green River downstream from the San Rafael River (gage 09328920, Green River at Mineral Bottom near Canyonlands National Park), and these gages reduce the ungaged watershed area to approximately 15,000 mi^2. These new data have not been used in the calculations of new water budgets for Lake Powell. The ungaged area could be further reduced by: (1) establishing a gage on the Colorado River downstream from the confluence with the Green River, perhaps near Hite, UT, (2) maintaining the present gages on the Dirty Devil River (gage 09333500, Dirty Devil River above Poison Spring Wash near Hanksville, UT) and Escalante River (gage 09337500, Escalante River near Escalante, UT), and (3) establishing remote stage recorders on the large ephemeral streams that drain into Lake Powell similar to the gages maintained by the USGS/GCMRC for ephemeral streams that drain the Marble Platform downstream from Lees Ferry[51].

Inflows to Lake Mead are better measured than at Lake Powell, because gage 09404200 is located only 15 mi upstream from Lake Mead and measures all regulated inflows from the Grand Canyon. The USGS also measures inflows of Diamond Creek (gage 09404208, Diamond Creek near Peach Springs, AZ), the Virgin River at gage 09415250 (Virgin River above Lake Mead near Overton, NV), Muddy Creek (gage 09419507, Muddy Creek at Lewis Avenue at Overton, NV), and Las Vegas Wash (gage 09419800, Las Vegas Wash below Lake Las Vegas near Boulder City, NV). Collectively, these gages measure stream flow from 94% of the contributing watershed area upstream from the measured outflow point from Lake Mead; inflows from 10,743 mi^2 remain ungaged.

4.7. *Findings*

The most recent data concerning evaporation rates – measured at Lake Mead between 2010 and 2015 using the eddy covariance methodology and estimated for Lake

Powell between 1965 and 1979 using the mass transfer methodology – indicate that the evaporation rate from Lake Mead may not be much greater than at Lake Powell. The surface area of Lake Powell is typically greater than the surface area of Lake Mead when the storage contents of the two reservoirs are the same. The estimated total evaporation losses from Lake Powell and Lake Mead may be less if FMF was implemented than under the present equalization rule, because the total evaporation losses are determined by multiplying the evaporation rate times the reservoir surface area. However, the uncertainty of these estimates is large. The measurements of evaporation rate at Lake Powell were made more than 35 years ago and are not comparable to the on-going measurements made at Lake Mead. **For purposes of public policy discussion at this time, we conclude that there would be no increase in evaporation losses if FMF were implemented.**

We find little support for Myers' (2013b) estimate that future losses from Lake Powell into ground-water storage will be ~0.30 million af/yr. Thomas (1986) estimated that the loss rate for the next few decades will be ~0.05 million af/yr and that the rate will decline further thereafter. However, these estimates are based on observations of ground-water conditions near Wahweap and around the north side of Glen Canyon Dam, and ground-water flow conditions since completion of Glen Canyon Dam have not been predicted for most of the area around the reservoir. **For purposes of public policy discussion at this time, we conclude that the annual rate of loss into long-term ground-water storage at times when Lake Powell is nearly full is ~0.05 million af/yr. this rate may be much less when reservoir elevation is lower.**

Assuming that losses into ground-water storage surrounding Lake Mead are small – an estimate suggested by water balance calculations but not by independent measurements of ground-water flow at wells – the projected water savings by implementing FMF are ~0.05 million af/yr. It is a matter of public policy debate as to whether or not this magnitude of savings is sufficiently large to justify immediate overhaul of many administrative and legal agreements, or to manage the challenging environmental issues that are discussed below. However, at some time in the future, perhaps this magnitude of water savings will be viewed as a large number worthy of serious engineering and scientific debate.

Initiation of a new measurement program of evaporation at Lake Powell, continuation of the present evaporation measurement program at Lake Mead, and initiation of a new phase of ground-water monitoring and modeling at Lake Powell and perhaps at Lake Mead would inform that future debate. Establishment of an eddy covariance measurement tower on Lake Powell would represent a modest investment to understand the magnitude of evaporation losses at Lake Powell. Establishment of new observation wells further from Lake Powell and to the south from Lake Powell, coupled by development of state-of-the-science numerical models of ground-water flow, would allow more precise estimates of future ground-water storage losses from the reservoir. Establishment on a new gaging station near Hite to reduce the amount of ungaged inflow to the reservoir and would allow more accurate water budgets to be developed. Collectively, these data would empower future water resource decision-makers to make critical decisions about reservoir management informed by much better data than exist today.

5. Effects of Draining Lake Powell on Remobilization of Fine Sediment in Lake Powell

5.1. *Fine sediment deposits in Lake Powell*

Fine sediment that once was transported by the Colorado River through Grand Canyon is now deposited in Lake Powell. Although modern estimates of fine sediment delivery into Lake Powell are not available, Topping et al. (2000) estimated that 54–60 million mt/yr (metric tons/year) was transported through Glen Canyon to Lees Ferry between 1949 and 1962, and it is reasonable to assume that this value as a good estimate of the present fine sediment delivery rate to Lake Powell; 40% of the fine sediment is sand. The source of the fine sediment is the upper Colorado, Green, Dirty Devil, Escalante, and San Juan Rivers, as well as smaller tributaries.

A challenge arises in estimating the volume occupied by this mass of fine sediment, and thus there is uncertainty in estimating how much of the storage capacity of Lake Powell is now filled by fine sediment. The bathymetry of Lake Powell has been occasionally surveyed, most recently in 1986 (Ferrari, 1988)[52] and between 2001 and 2005 (Pratson et al., 2008)[53]. Characteristics of the delta near Hite were measured by Majeski (2009)[54], and both deltas were photographed by Dohrenwend (2005)[55]. Ferrari (1988) estimated that 0.87 million af of fine sediment accumulated between 1963 and 1986 in Lake Powell, which is approximately 3% of the capacity of the reservoir; 54% of this fine sediment had accumulated near and upstream from Hite and 32% accumulated in the San Juan River arm.

Today, fine sediment deposits primarily occur as thick deltas near Hite in the Colorado River arm and in the San Juan River arm (Fig.25). The delta near Hite is formed by the fine sediment contributed by the Colorado and Dirty Devil Rivers, and the toe of the delta is approximately 125 mi (200 km) upstream from Glen Canyon Dam. The deltas of the Dirty Devil and Colorado are primarily composed of silt and clay and are cohesive. The delta of the San Juan River is about 60 mi (100 km) upstream from the dam (Pratson et al., 2008).

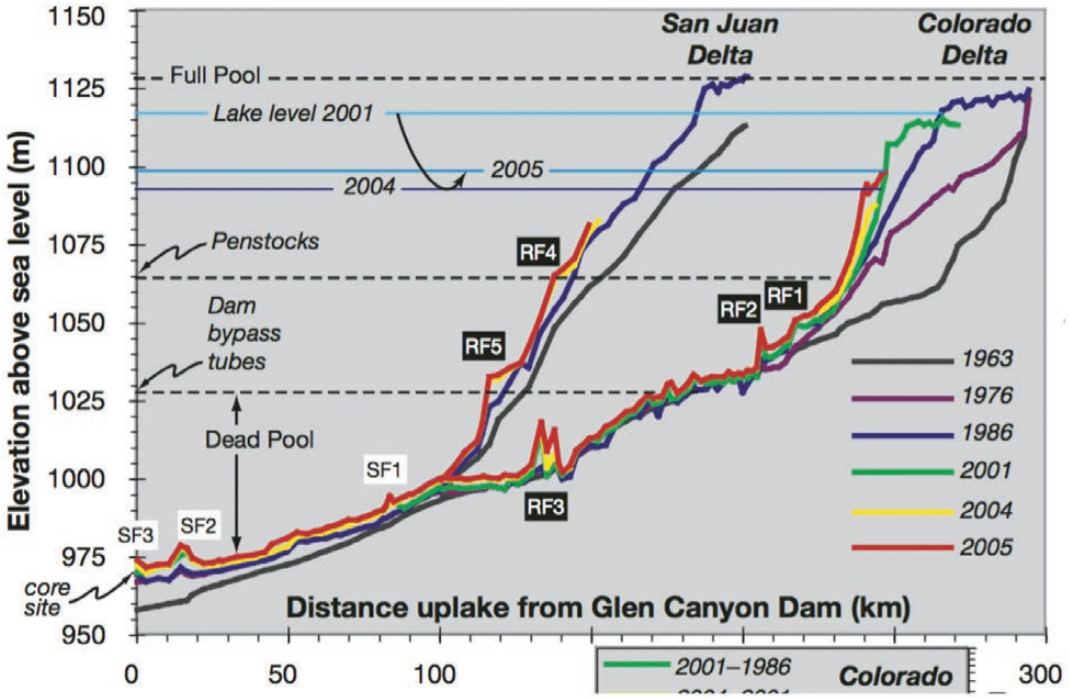


Figure 25. Graph showing the bathymetry along the centerline of the Colorado and San Juan arms of Lake Powell during successive surveys (Pratson et al., 2008, fig. 2A).

The upper elevation of these deltas is approximately the elevation of full pool, and the reservoir was most recently at this elevation in 1999. The upper surface of the delta of the Colorado River is between 50 and 200 ft above the former channel of the Colorado River. Majeski (2009) estimated that 0.41 million af of fine sediment accumulated in the Colorado River delta between 150 and 184 mi (~240 – 300 km) upstream from Glen Canyon Dam between 1963 and 1999 (Fig. 26). Most of the accumulated delta sediments occur at elevations higher than minimum power pool of 3490 ft asl that is the objective of Phase I of FMF. The entire delta of the Colorado River occurs above dead pool elevation of 3370 ft asl, which is the objective of Phase II of FMF.

The drawdown of the reservoir that occurred between 1999 and 2005 lowered the reservoir by approximately 180 ft to an elevation of 3560 ft asl (Fig. 27), which is 70 ft higher than the objective of Phase I of FMF but nevertheless was the largest drawdown of the reservoir in its history. Observations made during this drawdown provide insights about what might happen if FMF was implemented.

Between 1999 and 2005, approximately 0.084 million af of fine sediment was remobilized in the Colorado River delta, because the Colorado River eroded a new channel into its delta (Fig. 28); the sediment that was remobilized comprised approximately 20% of the volume that had accumulated during the previous 36 years. About 35% of this eroded sediment was redeposited immediately on front of the delta, and the rest of this fine sediment was transported beyond the toe of the delta, much closer to the dam. Majeske (2009) estimated that 15% of the delta of the Dirty Devil River was remobilized.

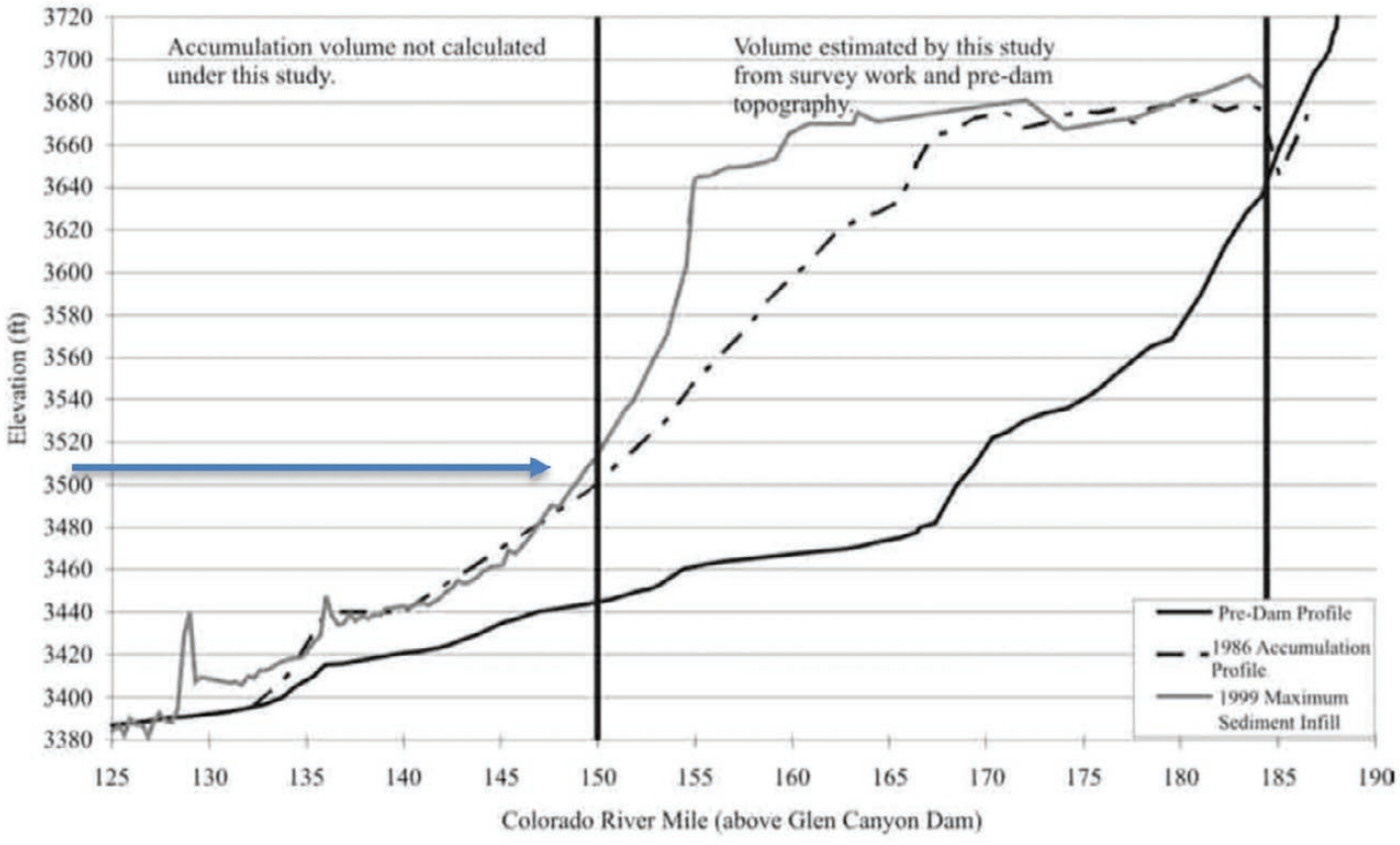


Figure 26. Graph showing longitudinal profile of the Colorado River before completion of Glen Canyon Dam and the topography of the delta surface in 1986 and 1999, based on measurements by Ferrari (1988) and Pratson et al. (2008) (from Majeski, 2009, fig. 58). Blue arrow indicates the elevation of minimum power pool.

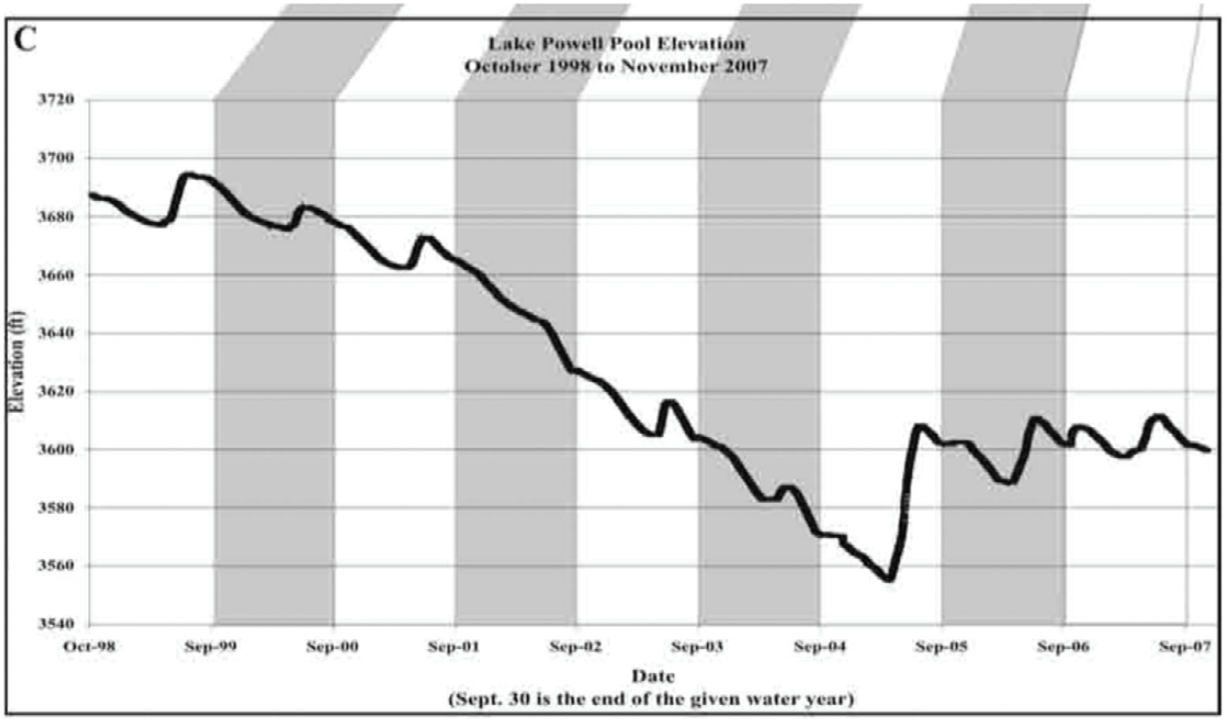


Figure 27. Graph showing elevation of Lake Powell during the period when bathymetric measurements described remobilization of fine sediment in the reservoir's deltas (from Majeski, 2009, figure 1C).

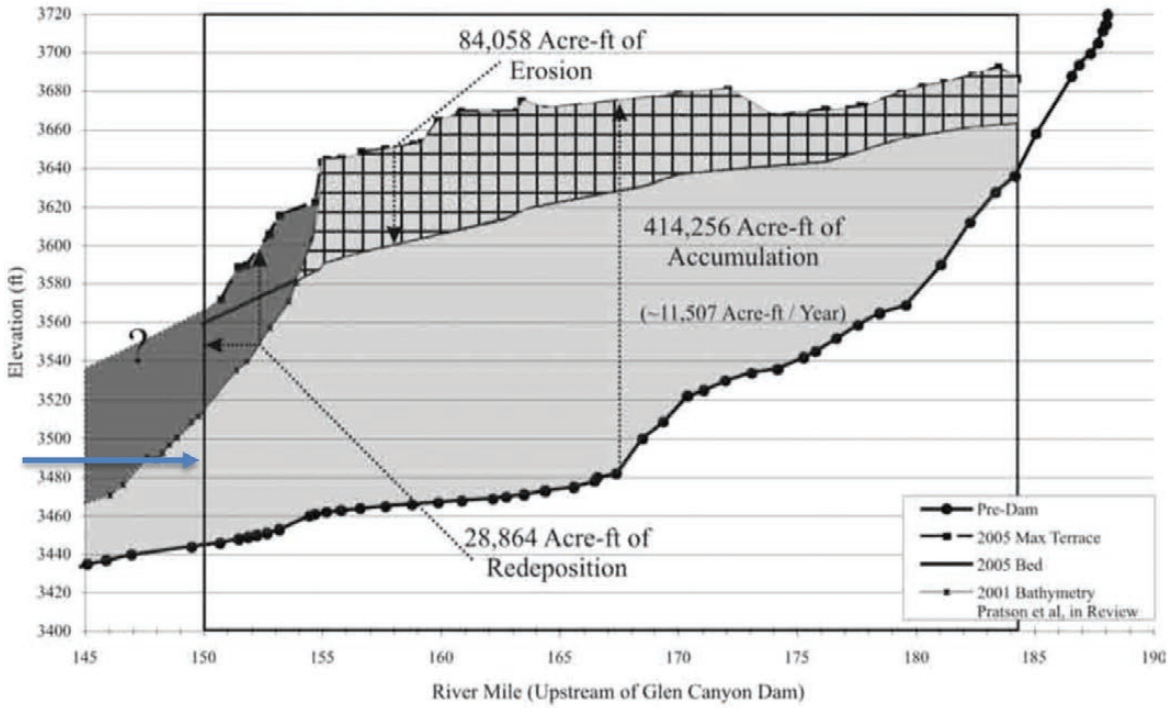


Figure 28. Graph showing accumulation between 1963 and 1999 and evacuation between 1999 and 2005 of fine sediment from the Colorado River delta (Majeske, 2009, fig. 57). Blue arrow indicates the elevation of minimum power pool.

Pratson et al. (2008) measured the same processes (Fig. 29), and he demonstrated that the Colorado River delta advanced (called "progradation") into the reservoir ~40 mi. Majeske (2009) focused on the erosional processes that occurred on the upper surface of the delta, and Pratson et al. (2008) focused on measurements of bathymetric change in the entire reservoir; the data of the two studies are complementary. Pratson et al. (2008) showed that some of the fine sediment was transferred away from the deltas by turbidity currents (also called hyperpycnal or subaqueous-gravity flows), but these deposits primarily accumulated upstream from 3 rockfalls that now fill part of the reservoir bottom (labelled RF1, RF2, and RF3 in Fig. 25 and 29); little fine sediment was transported closer to Glen Canyon than RF3. In contrast, the delta of the San Juan River did not significantly prograde into the reservoir during the drawdown period, but fine sediment eroded from the upper surface of that delta was transported to the base of Glen Canyon Dam by turbidity currents.

Based on his bathymetric measurements but not on the supplemental data of Majeske (2009), Pratson et al. (2008) estimated that approximately 0.81 million af of fine sediment was redistributed from the deltas of the Colorado and San Juan deltas to the interior parts of the reservoir that are below the elevation of "dead pool." Pratson et al. (2008) estimated that the mass of this fine sediment redistribution was approximately 1000 x 10^6 mt, which is approximately 18 years of average fine sediment delivery to the reservoir, based on Topping et al.'s (2000) data.

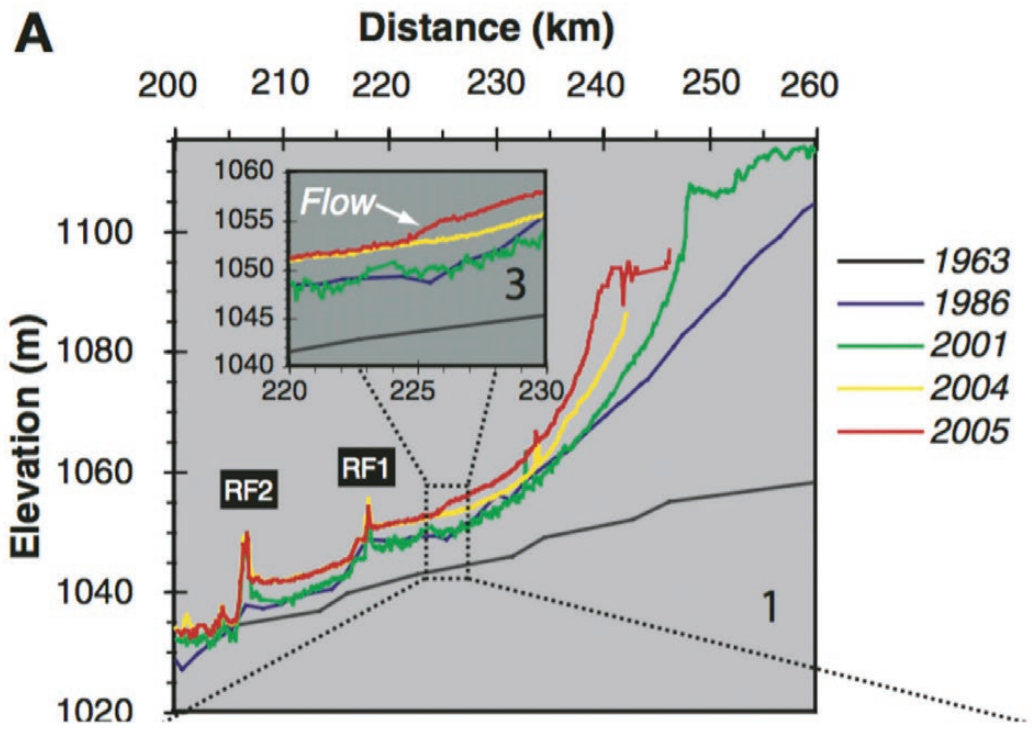


Figure 29. Graph showing the bathymetric profile of the Colorado River delta at different times (Pratson et al., 2008, Fig. 3A). The distance of 240 km shown on this graph is equivalent to a point 150 miles upstream from Glen Canyon Dam shown on the graphs of Majeske (2009).

5.2. *Findings*

The observations made between 1999 and 2005 demonstrate that significant remobilization of fine sediment would occur in Lake Powell during reservoir draining of Phase I and Phase II. Most of the remobilized fine sediment would be deposited in new deltas that would form in the partially drained reservoir. Turbidity currents would carry some of that fine sediment to the base of the dam. Rockfalls that now fill parts of the reservoir bottom have the potential to block turbidity currents from transporting fine sediment from the Colorado River arm to the dam, but turbidity currents would carry fine sediment from the San Juan River delta to the base of the dam.

There is no doubt that the Colorado and San Juan River channels would incise into their respective deltas. In some cases, the incision would primarily be vertically downward and leave large tracts of flat-lying delta surface perched high above a deep, narrow channel; in other cases, the ever deepening channel would also widen and remove larger parts of the delta deposit. Majeske (2009) showed that approximately 50% of the small delta of North Canyon Wash was eroded during the 1999-2005 drawdown, but he also showed that much less of the Dirty Devil and Colorado deltas were eroded. Between 1999 and 2005, the Dirty Devil River vertically incised its channel approximately 30 ft below the upper surface of the delta, and there was little lateral movement or channel widening. Large areas of the Dirty Devil delta remained high above the incised channel and were not removed by erosion. In contrast, the Colorado River incised its bed approximately 50 ft below the upper surface of its delta, and a larger proportion of the upper surface of the delta was also eroded. In some places, such as near Hite, parts of the Colorado River delta experienced lateral slumping or lateral spreading (Fig. 30). Dohrenwend (2005) showed that lateral slumping was more active immediately after a rapid decrease in reservoir elevation or during periods of high Colorado River inflows.

The incising channels do not necessarily reoccupy the former channels. In the San Juan River arm, the San Juan River now flows over a bedrock ledge that blocks upstream migration of fish and downstream navigation. Pearce Ferry Rapids in Lake Mead occurs where the Colorado River sweeps around a bedrock ledge. It may be impossible to predict whether or not additional ledges are encountered as Lake Powell is drained.

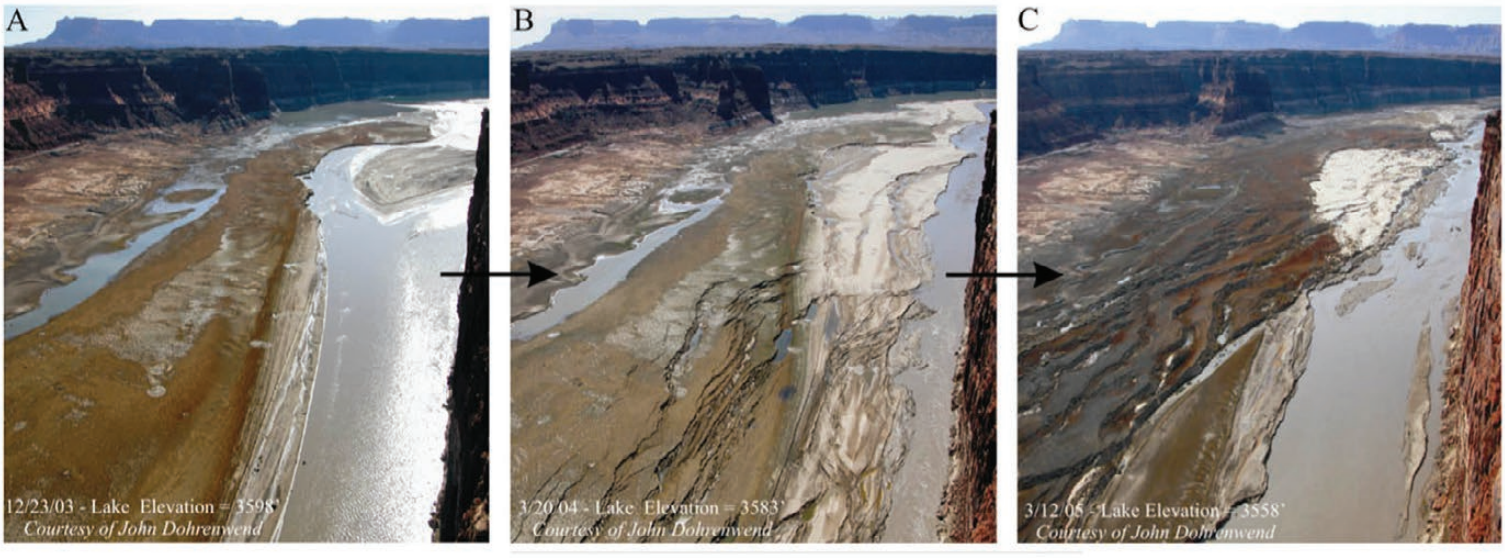


Figure 30. Photographs taken from the Hite Overlook showing lateral slumping and lateral spreading near Hite. A and B show slumping induced by a 15-ft drawdown that occurred during a 3-month period in 2003 and 2004. C shows further slumping that occurred during a 12-month period following the photograph shown in B. all photographs courtesy of J. Dohrenwend (reprinted by Majeski, 2009, figure 46).

The differences in the extent and characteristics of delta erosion during reservoir drawdown demonstrate that it is difficult to predict the extent to which the deltas of the Colorado, Dirty Devil, and San Juan Rivers would be remobilized if FMF were implemented. Although observations in small tributaries of Lake Powell have demonstrated that large amounts of post-drawdown erosion exposed the underlying slot canyons, this will likely not be the case in the deltas of the Colorado, Dirty Devil, and San Juan Rivers. Numerical and physical modeling might inform reservoir drawdown strategies that would facilitate the goals of FMF.

The bathymetric data of Pratson et al. (2008) demonstrate that much less fine sediment has accumulated in the deep parts of Lake Powell that are much closer to Glen Canyon Dam. These are the areas that are within Glen Canyon itself and that are the primary restoration goal of the GCI. The challenge to restoration of Glen Canyon, however, is that the inevitable incision of the deltas near Hite and in the San Juan arm will redistribute fine sediment and deposit new deltas in the smaller Lake Powell created during Phase I.

Another wave of redistribution would occur when Phase II was implemented and reservoir elevations were established at dead pool elevation of 3370 ft.

There is no way to prevent deposition of new deltas under Phase I or II of FMF, because delta formation is inevitable wherever rivers with large sediment loads enter reservoirs. Lowering the elevation of Lake Powell and preferentially filling Lake Mead will increase sedimentation in the parts of Glen Canyon that remain inundated. The rate at which this new wave of reservoir sedimentation occurs is uncertain Eventually, sedimentation will affect flow into the river outlets at 3370 ft asl. If Phase III of FMF was implemented and new diversion tunnels were drilled, near-dam reservoir sedimentation would be of even greater concern. Although these issues may not be insurmountable, they would require significant engineering design and careful planning so as not to jeopardize the restoration goals of FMF. **For purposes of public policy discussion, the partial or complete draining of Lake Powell would pose a significant issue regarding the ultimate fate of the newly exposed sediments. Under Phase I and Phase II, new deltas of fine sediment would form within Glen Canyon closer to the dam.**

6. Impacts to the Grand Canyon Ecosystem

6.1. Thermal and stream-flow regime of the Colorado River under if Fill Mead First was implemented

We developed a simple stream-flow and reservoir-storage model to evaluate the downstream changes in stream flow and river temperature that would occur if FMF was implemented, based on the assumed implementation strategies described above. The existing stream-flow regime of the Colorado River includes:

- significant flood control caused by storage of the spring snowmelt flood in Lake Powell and the release of most flow through the power-plant turbines and occasional release of additional water through the river outlets to create High Flow Experiments (HFEs), hereafter called controlled floods;
- distribution of monthly flows to match regional electricity demand that is greater in winter and summer;
- distribution of daily flows to match daily patterns of electricity demand; and,
- base flows that typically exceed 8000 ft^3/s.

The thermal regime of released reservoir water fluctuates annually, but much less than during pre-dam times (Fig. 4). The thermal regime of the Colorado River in the Grand Canyon ecosystem primarily is determined by the volume of water stored in Lake Powell, because water is withdrawn at the fixed elevations of the power-plant penstocks. When the reservoir is relatively full, withdrawn water is cool in relation to typical pre-dam summer water temperatures; when the reservoir is relatively empty, withdrawn water is much warmer. Because Lake Powell would be much smaller under Phase I of FMF, summer water temperature released into the Grand Canyon ecosystem would be higher in summer than occurs today; releases in winter might be cooler. Summer releases under Phase II would be even warmer than under Phase I at those times when dead pool conditions existed. Because reservoir release temperatures will depend on the thermal stratification of the partially drained Lake Powell, and because we predict that reservoir storage contents would fluctuate during years of large inflows, it is difficult to predict the annual temperature regime of the Colorado River under Phase I or II. In light of the implications of the thermal regime to the behavior and distribution of native and nonnative fish in the Grand Canyon ecosystem, predictive modeling of the ecological implications of likely thermal modifications is appropriate.

As described above, the stream-flow regime downstream from Glen Canyon Dam would have the potential to be greatly changed by implementation of Phase I, but the extent of change partly depends on whether or not hydropeaking is de-emphasized; hydropeaking does not necessarily have to be de-emphasized, because the power-plant turbines remain operational. In Phase II, annual stream flow would be very steady, but controlled floods of 45,000 ft^3/s could still be released whenever reservoir elevation rose from dead pool to 3490 ft asl.

6.1.1. Temperature of the Colorado River if FMF was implemented

Releases from large reservoirs typically moderate the thermal regime of downstream rivers, because water is released from a thermally stratified reservoir (Fig. 3). Water is typically released from the hypolimnion, the lower part of a reservoir where water is cooler in summer and warmer in winter than the surface waters. Thus, reservoir releases typically increase winter temperatures, decrease summer temperatures, and reduce the annual variability of river temperatures (Olden and Naiman, 2012)[56]. Pre-dam temperatures in the Colorado River downstream from Glen Canyon Dam once ranged between about 35°F in winter to 75°F in summer, and the highest water temperatures typically occurred in August. Post-dam temperatures typically have been between 45°F and 55°F year round (Fig. 4). Releases begin warming in May and June and are warmest in November or December (Vernieu et al. 2005). Before 1973, during the period when Lake Powell was filling for the first time, the annual water temperature regime was similar to pre-dam conditions, because lake levels were

close to the elevation of the penstocks (Vernieu et al., 2005). Between 1973 and 2003, released water temperature was colder, because virtually all reservoir water was withdrawn from the hypoliminion. In 2003 and 2004, Lake Powell reached a low level of 3564 ft asl, and the maximum annual water temperature of reservoir releases was 59.9°F in October 2004 (Fig. 4) (Vernieu et al., 2005). In 2005, Lake Powell reached its lowest level in the last 30 years of 3555.9 ft asl, and the highest annual temperature at Lees Ferry was 61°F in October 2005 (Anderson and Wright, 2007)[57]. Between 2014 and March 2016, reservoir level varied between 3574 and 3613 ft, asl, and water temperature at Lees Ferry ranged from 46°F and 60°F.

Although the primary determinant of Colorado River temperature is the temperature of the released reservoir water and the volume of that release, water temperatures increase downstream, because the river is warmed by direct sunlight and warm summer air. Wright et al. (2009)[58] summarized these effects, and developed an algorithm to predict the increase in river temperature of a reservoir release of 48°F and an air temperature of 79°F. Figure 31 summarizes the predicted river temperature near the mouth of the Little Colorado River (RM 65), which is the area of densest concentration of humpback chub. For example, if reservoir releases are 59°F (15C) and the monthly releases are 0.35 million af, then the Colorado River's temperature at RM 61 is predicted to be 68°F (20C); if the monthly releases are 0.75 million af, then the Colorado River temperature at RM 61 is predicted to be 64°F (18C).

In Phase I of the FMF plan, summer reservoir release temperatures would be higher than those modeled by Wright

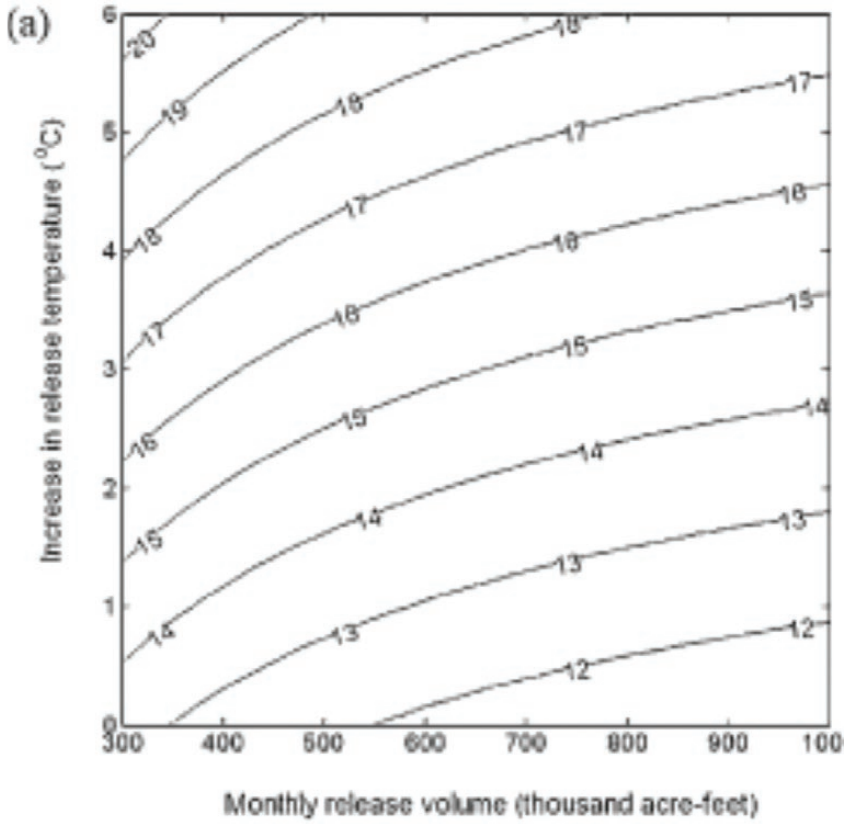


Figure 31. Graph showing predicted temperature near RM 61 as a function of the temperature of the water released from Lake Powell and the monthly volume of those releases. Values shown on contour lines are the predicted water temperature, in C, near the confluence of the Colorado and Little Colorado Rivers. Values on the x axis are the monthly volume of water released from Lake Powell. Values on the y axis are degree of warming of reservoir releases greater than typical releases of 48F (9C), in 1C (1.8F) increments. Simulations are for typical summer conditions where mean daily air temperature is 79F (Wright et al. 2008).

et al. (2008). A reservoir elevation of 3490 ft asl has not occurred since the mid-1960s, and releases at that time retained the annual temperature cycle of the pre-dam river (Fig. 4). The rate of downstream warming would depend on the monthly volume of releases. If Phase I releases were similar to those depicted in Figure 31, there would be little warming during the weeks when 45,000 ft^3/s was being released, but releases would warm about 7°F (4C) when monthly releases were about 8000 ft^3/s per day.

6.1.2. The Colorado River's flow regime if FMF was implemented

A reservoir model of simulated storage in Lake Powell was developed using the Water Evaluation and Planning (WEAP) software to simulate the multi-year reservoir fluctuations and flow regime of Phase I and Phase II. The measured monthly inflow between 1963 and 2015 was used in this simulation; the data were obtained from http://www.usbr.gov/rsvrWater/faces/rvrOSMP.xhtml. In each simulation, we used the evaporation coefficients of Jacoby et al. (1977) (Table 2) and the reservoir elevation – storage volume relationship used by Reclamation (2007). Model simulations for Phase I assumed an initial elevation of 3490 ft asl. We assumed that the reservoir management objective was to release water at the same rate as inflows whenever possible (i.e., run-of-the-river). We assumed that the maximum release could not exceed 45,000 ft^3/s. We did not consider a release pattern that included fluctuations to maximize the value of hydropower, and we did not consider an objective to maintain a specific reservoir elevation or storage volume.

Although the objective of Phase I is to maintain reservoir elevation at 3490 ft asl, there will inevitably be times when the reservoir would rise above this level, because inflows exceed outflows in years of large snowmelt runoff. Based on the monthly inflow sequence that occurred between 1963 and 2016, such conditions would occur in approximately 30% of all years (Fig. 32). The maximum elevation to which the reservoir would rise under this inflow scenario would be 3560 ft asl, approximately 70 ft higher than the objective of Phase I. Outflows from Lake Powell would mimic run-of-the-river conditions. but the maximum magnitude of floods would never exceed 45,000 ft^3/s (Fig. 33). Nevertheless, most of the monthly flow characteristics of the inflow regime would be preserved in the outflow regime.

Reservoir elevations would fluctuate much more widely if Phase II was implemented, primarily because the maximum release of water cannot exceed 15,000 ft^3/s if reservoir elevations are less than 3490 ft asl (Table 1). Assuming that monthly inflows were the same as those that occurred between 1963 and 2016, reservoir elevations would vary by nearly 200 ft, and reservoir elevation would exceed the target elevation of 3370 ft asl for many years during periods of high inflows (Fig. 34). In fact, reservoir elevations would rarely be at 3370 ft asl. The flow regime of the Colorado River in the Grand Canyon ecosystem would be dominated by steady flows less than 15,000 ft^3/s with short periods when floods of 45,000 ft^3/s when reservoir elevations exceeded 3490 ft (Fig. 35). We modeled projected outflows assuming that inflows were the same as those that occurred between 1963 and 2016. Because the rate of discharge through the river outlets is dependent on reservoir elevation (Table 1), monthly flows less than 15,000 ft^3/s would occur much of the time and the most frequently occurring monthly discharge would be 12,600 ft^3/s (Table 7).

It should be noted that the decrease in total reservoir storage that is associated with establishing Lake Mead as the primary storage facility would necessitate careful consideration of water allocation agreements between the Upper and Lower Basin. The WEAP model results described above do not consider any limitations on the delivery rate of water from the Upper Basin. Thus, more than 8.23 million af are hypothetically transferred to the Lower Basin in many years using the scenarios described above, because the hydrology of the 1963-2016 period is assumed (Fig. 36). Such transfers would not occur if there were any risk of exceeding the storage capacity of Lake Mead. These results highlight the need to develop new operating rules that would allow the goals of FMF to be achieved while not jeopardizing regional water supply security.

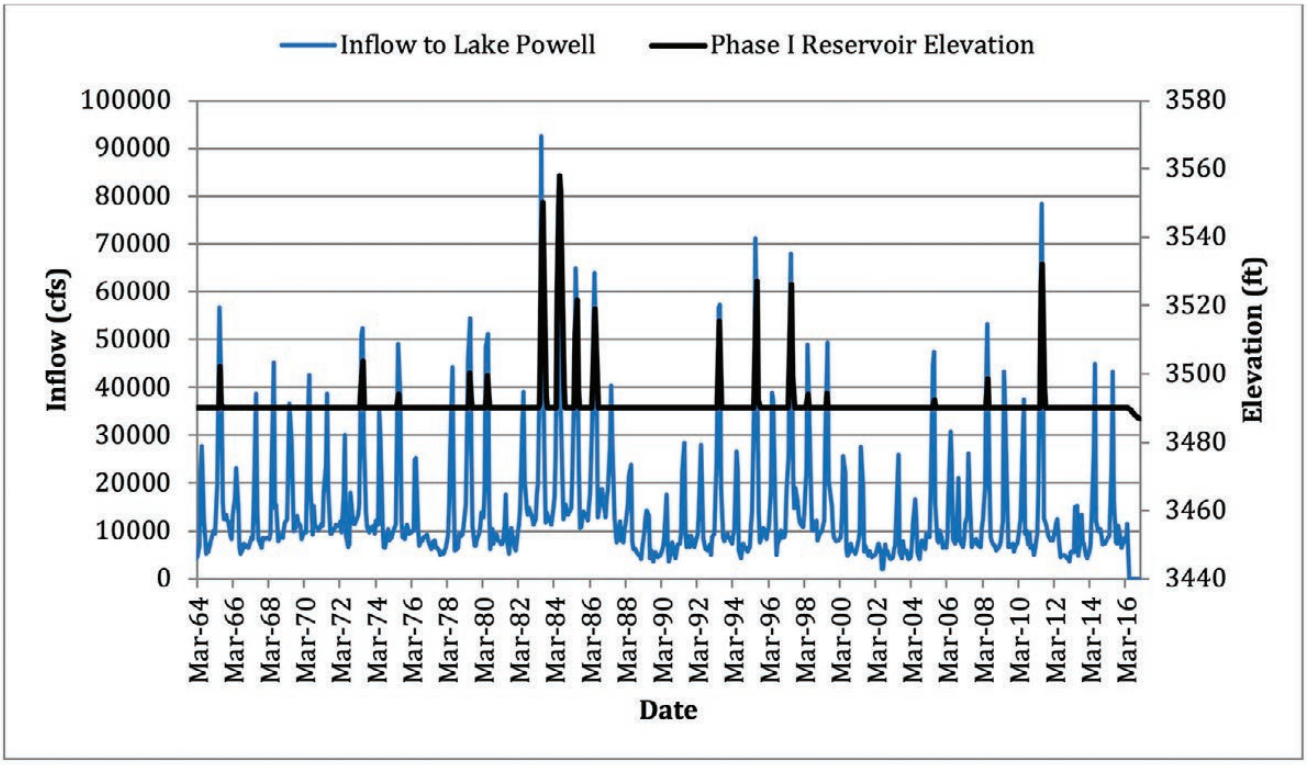


Figure 32. Graph showing the projected elevation of Lake Powell if Phase I were implemented and monthly inflows were the same as those that occurred between 1963 and 2016, based on WEAP modeling and assumptions described in text.

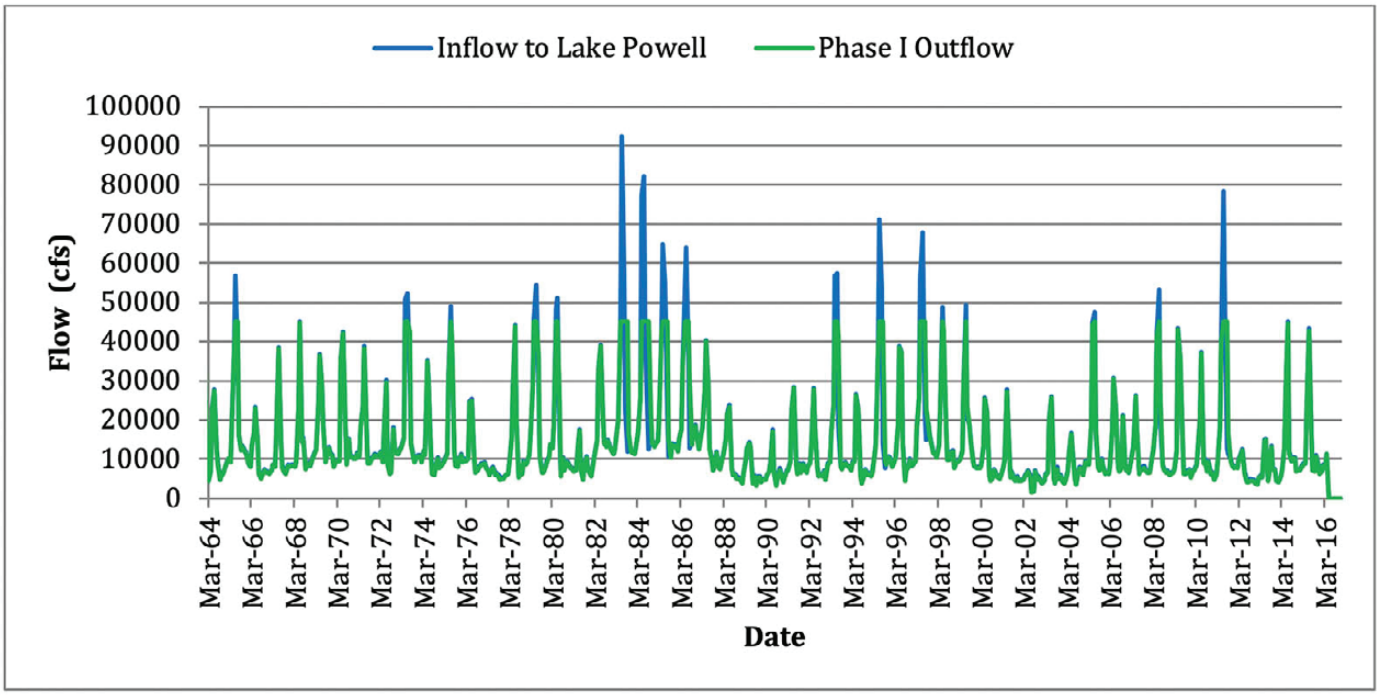


Figure 33. Graph showing inflows and outflows from Lake Powell under Phase I of FMF, assuming monthly inflows were the same as those that occurred between 1963 and 2016, based on WEAP modeling and assumptions described in text.

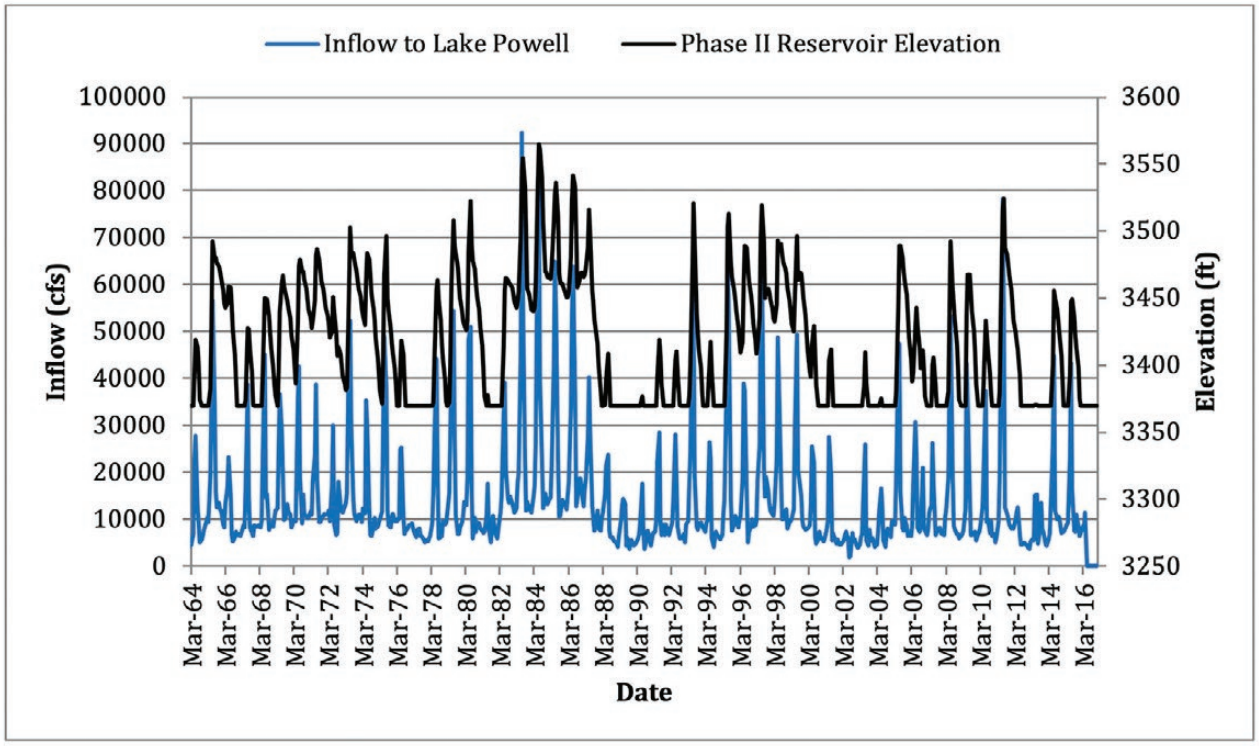


Figure 34. Graph showing the projected elevation of Lake Powell if Phase 2 were implemented and monthly inflows were the same as those that occurred between March 1963 and March 2016, based on WEAP modeling and assumptions described in text.

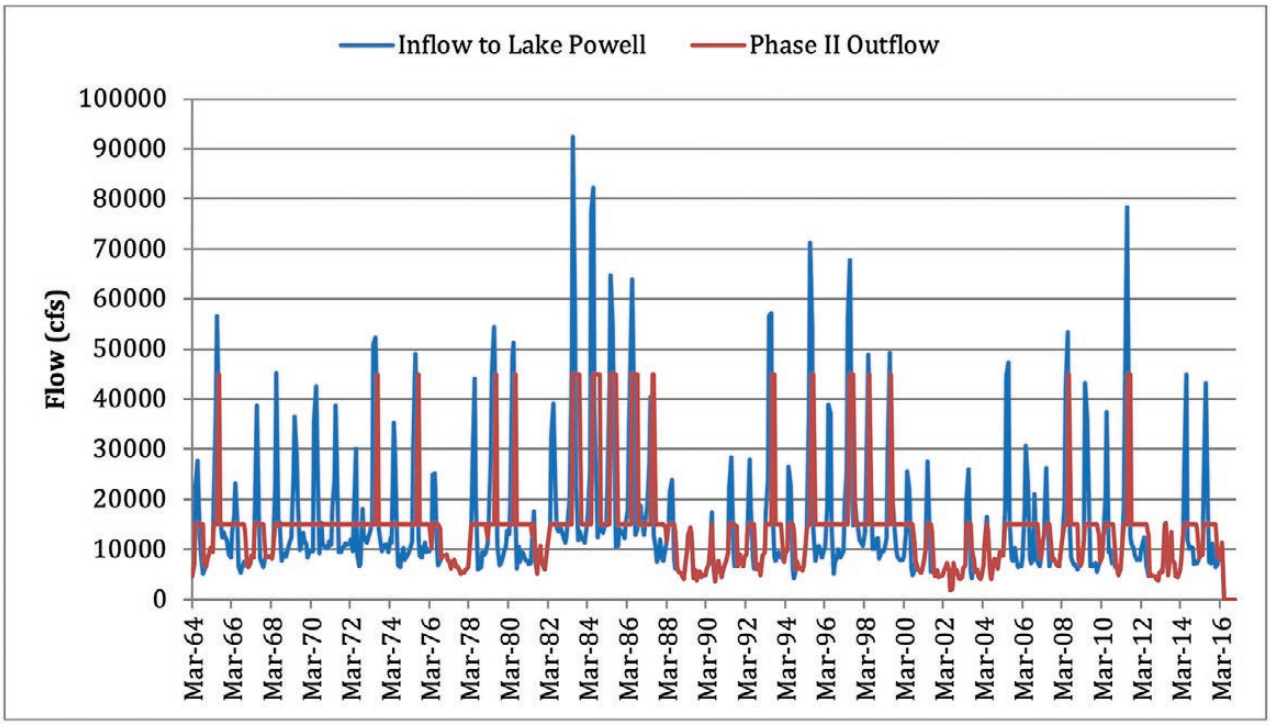
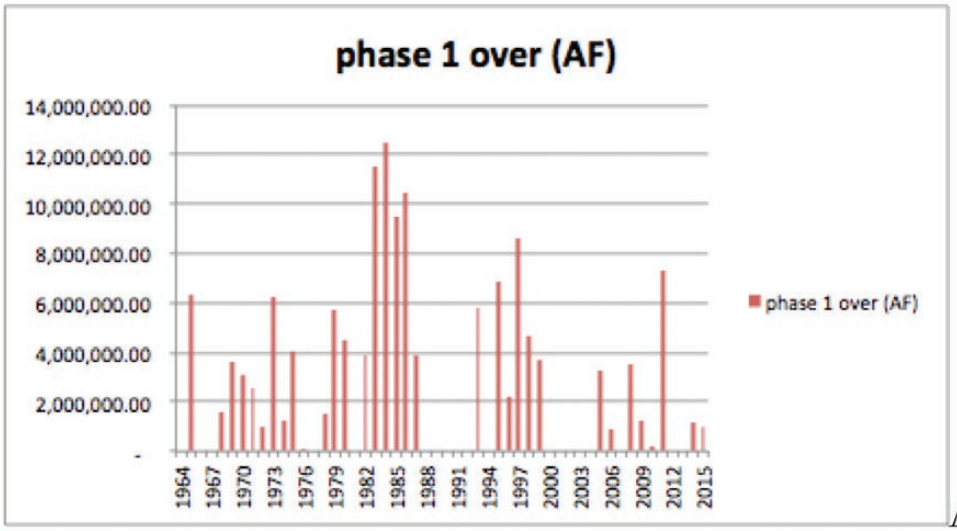


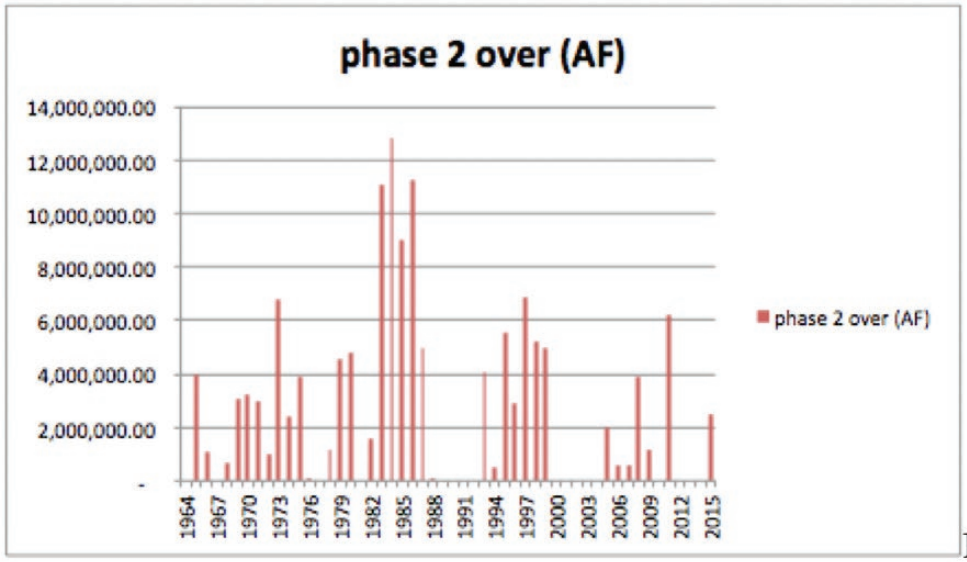
Figure 35. Graph showing inflows and outflows from Lake Powell under Phase 2 of FMF, assuming monthly inflows were the same as those that occurred between March 1963 and March 2016, based on WEAP modeling and assumptions described in text. Reservoir releases from Lake Powell would never exceed 15,000 ft^3/s unless reservoir elevations exceeded 3490 ft asl, when 45,000 ft^3/s could be released.

Table 7. Duration of mean monthly flows that would occur under Phase II if the inflows were the same as those that occurred 1963-2016.

Reservoir release under rules of Phase II, in cubic feet per second	Percent of time indicated mean monthly flow would occur, assuming inflow hydrology was the same as that which occurred 1963-2016
45,000	9.5
14,600	6.3
12,600	41.6
11,400	8.7
10,200	10.8
8,800	11.9
4,800	11.2



A



B

Figure 36. Graphs showing the volume of water in excess of 8.23 million af that would be transferred downstream under (A) Phase I and (B) Phase II of FMF, assuming that the inflow hydrology wre the same as that which occurred between 1963 and 2016.

6.2. *Impacts of FMF on the Colorado River ecosystem in Grand Canyon*

One of the stated benefits of the FMF proposal is that the Grand Canyon ecosystem would benefit by re-establishing a run-of-the-river flow regime and would benefit from a more natural temperature and sediment supply regime. There is no doubt that native ecosystem attributes and processes will be very different if FMF was implemented, but the ecosystem that presently exists in the Grand Canyon segment is no longer dominated by the ecosystem processes that existed prior to 1963. The present ecosystem has been described in an extensive literature (see reviews by Gloss et al., 2005; Melis et al., 2010[59]; Melis, 2011[60]), and review of that literature is beyond the scope of this paper. Here, we describe the most significant changes that would occur to the Grand Canyon ecosystem. Undoubtedly, these changes would initiate intended, and unintended, consequences to the native, and non-native, river ecosystem. Monitoring would have to proceed in a deliberate way and be conducted during decades to ensure that the status of endangered species and of valued national park resources were not jeopardized by the pace and extent in which FMF was implemented.

6.2.1. Stream-flow, sediment-supply, and thermal regimes

The flow regime of the Colorado River would not be run-of-the-river under Phase I or Phase II. Under Phase I, floods would not be larger than 45,000 ft^3/s, but their duration would be longer than the duration of natural floods. The duration of these floods would be much longer than the duration of HFEs; floods released if FMF was implemented would occur in late spring which is the time of year when the natural annual peak flow occurs. Although not analyzed here, it is possible that some monsoon season floods generated in the San Juan River watershed or elsewhere in southeast Utah might be passed downstream. Under Phase II, the flow regime in Grand Canyon would not simulate natural conditions, because the releases downstream are limited by the capacity of the river outlets. In order to meet the objectives of a partially drained Lake Powell, it would be necessary to release nearly steady flows through the river outlets and occasionally release 45,000 ft^3/s floods whenever Lake Powell rose to 3490 ft asl. Such floods might occur at times completely out of the natural flood cycle. **Only under Phase III, and assuming that large capacity diversion tunnels are drilled around the dam, might the natural flow regime of the Colorado River in Grand Canyon be restored.**

The sediment supply regime of the Colorado River is a problematic aspect of the FMF proposal. Because Lake Powell would continue to exist in a partially drained condition under Phase I and Phase II, reservoir sedimentation would continue, and clear water would be released downstream. Thus, the Grand Canyon ecosystem would persist in fine sediment deficit. It is beyond the scope of this paper to evaluate whether or not the long-duration 45,000 ft^3/s floods that would occur under Phase I and Phase II would exacerbate sediment deficit conditions and initiate more sand bar erosion. Nevertheless, this is a possibility, because long-duration controlled floods would occur every year regardless of whether or not new sand supplies had been delivered from the Paria River. The present HFE Protocol only schedules controlled floods when the Paria River has delivered new sand to the Colorado River, and the duration of controlled floods is only long enough to mobilize and redistribute that sand.

Under Phase III, however, the fine sediment mobilized from the eroding deltas of a drained Lake Powell would become source areas that would supply a large amount of fine sediment into Grand Canyon. Thus, under Phase III of FMF, the eddies of Grand Canyon would probably fill with fine sediment, much of the channel bed might be covered by fine sediment, gravel substrate in Glen Canyon near Lees Ferry would be buried in fine sediment, and the river would be more turbid. It is likely that the eroding deltas of Lake Powell would continue to be source areas for downstream areas for decades.

The thermal regime of the Colorado River in the Grand Canyon ecosystem would become more similar to that of the

natural river, although the degree to which this occurs would depend on the thermal stratification of the reservoir. There were large annual fluctuations in the temperature of reservoir releases in the late 1960s when Lake Powell was last at 3490 ft asl (Fig. 4). It is likely that thermal conditions of reservoir releases would have nearly natural annual temperature fluctuations under Phase II, and would certainly be natural conditions under Phase III.

6.2.2. Aquatic ecosystem

The primary change in the aquatic ecosystem under Phase I would be caused by the long duration high flows and the much lower flows that would occur in fall and winter in some years. The more natural thermal regime would cause changes in the distribution of native and non-native fish populations, and the potential for significant upstream invasion by warm-water non-native fish. Some of these non-natives might compete or be predatory on native fish, including humpback chub. The unusual flow regime of Phase II might have consequences on the aquatic food base and on the populations of fish. Under Phase III, the entire aquatic ecosystem would have the potential to change radically. There is no way to predict the relative benefit to native and non-native fish species; in the upper Colorado River basin where natural flow regimes still exist, most of the fish biomass is non-native fish.

6.2.3. Findings

The magnitude of these changes is so great that partial or complete draining of Lake Powell could only be undertaken if pursued adaptively wherein monitoring data would be collected and reviewed, and the trajectory of the ecosystem be continually predicted and evaluated. Partial or complete draining would exert an enormous ecosystem stress on the Grand Canyon, and the relative benefit to native and non-native species is impossible to predict. The present ecosystem is a mix of native and non-native processes, and the stresses to the existing ecosystem would be unprecedented.

GCI has proposed that the Glen Canyon Dam Adaptive Management Program (GCDAMP) could be eliminated if FMF was implemented, because natural stream-flow conditions would be re-established in Grand Canyon. It is unlikely that ecosystem monitoring could be eliminated when the stream-flow, sediment-supply, and thermal regimes of the Colorado River in Grand Canyon would be drastically changed from the conditions that have existed for more than 50 years. These changes in stream flow and water quality have the potential to greatly change ecosystem processes and characteristics in the Grand Canyon, greatly affecting the endangered humpback chub and razorback sucker (*Xyrauchen texanus*) as well as the recreational rainbow trout fishery that presently exists between the dam and Lees Ferry. It is unlikely that federal or state agencies would allow FMF to proceed without ecosystem monitoring to evaluate the effects of reservoir draining on these fish populations**. It is also unlikely that monitoring of conditions in Grand Canyon National Park would be abandoned when such dramatic changes in the Colorado River were occurring. We discount the assertion that $10 million/yr would be saved by the elimination of the GCDAMP.**

7. Acknowledgements

The effort began as a class project in *Large River Management: the Colorado River*, a 2016 spring-term graduate course in the Department of Watershed Sciences. An earlier version of this white paper was carefully reviewed by Johnnie Moore whose comments inspired significant revision and improvement. Helpful comments and discussion were received from Cory Angeroth, Eric Balken, Anne Castle, Rick Clayton, Richard Ingebretsen, Douglas Kenney, Stan Leake, Larry MacDonnell, James Mauch, Scott McComb, Mike Moreo, Tom Myers, Colby Pelegrino, and Bradley Udall. Support for the Center for Colorado River Studies is provided by My Good Fund, David Bonderman, and the Janet Quinney Lawson Foundation.

8. Endnotes

1. Available at http://www.usbr.gov/lc/region/g1000/pdfiles/opcriter.pdf.

2. Available at http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf.

3. Kellett, M. 2013. Fill Mead First: a plan for saving Colorado River water & beginning the restoration of Glen and Grand Canyons. *Hidden Passage, the journal of Glen Canyon Institute*, issue XIX: 4-6.

4. Beard, D. P. 2015. Deadbeat dams: why we should abolish the U. S. Bureau of Reclamation and tear down Glen Canyon Dam. Boulder, CO, Johnson Books, 143 p.

5. Lustgarten, A. 2015. Killing the Colorado. Propublica, available at <https://www.propublica.org/series/killing-the-colorado>.

6. Lustgarten, A. 2016. Unplugging the Colorado River. *The New York Times*, available at <http://www.nytimes.com/2016/05/22/opinion/unplugging-the-colorado-river.html>.

7. The location system for the Colorado River in the Grand Canyon region is a system that was established in the 1920s by the U. S. Geological Survey. Locations downstream from Lees Ferry are described by the distance in river miles downstream from Lees Ferry (in positive numbers) and locations upstream from Lees Ferry are described by the distance upstream from Lees Ferry (in negative numbers) to Glen Canyon Dam. Elsewhere in this report, we describe locations in Lake Powell in distance, in miles, upstream from the dam.

8. Gloss, S. P., Lovich, J. E., and Melis, T. S., eds. 2005. The state of the Colorado River ecosystem in Grand Canyon. *U. S. Geological Survey Circular* 1282, 220 p.

9. "Fine sediment" means sand, silt, and clay. Deposits of silt and clay are sometimes called "mud."

10. Topping, D. J., Schmidt, J. C., and Vierra, L. E., Jr. 2003. Discharge of the Colorado River at Lees Ferry, Arizona, during the 1884 flood and between May 8, 1921, and September 30, 2000: construction and analysis of a continuous record of instantaneous discharge: *U. S. Geological Survey Professional Paper 1677.*

11. Bureau of Reclamation. 1989. Lake Powell reservoir capacity allocations, Fig. IV-1.

12. Bureau of Reclamation. 2010. Glen Canyon Dam comprehensive review report. Salt Lake City.

13. Bureau of Reclamation data accessed here.

14. Fedarko, K. 2013. The Emerald Mile. New York, Scribner, 415 p.

15. Information available online at: http://www.usbr.gov/lc/region/g1000/lawofrvr.html.

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32. Myers (2013b) states that "The total current loss ranges from 1.6 to 1.8 maf/yr," but the higher end of this range cannot be computed from the data Myers used.

33. Myers (2010) estimated this value to be 0.12 million af/yr, but he estimated that there would be a small amount of additional losses associated with evapotranspiration from the hillsides newly exposed in Glen Canyon.

34. Myers (2013b) states that, "The savings due to Fill Mead First would vary from 0.3 to 0.6 maf/y depending on the exact loss rates and the target volume for Lake Powell." We can replicate the value of 0.6 million af/yr only by using the high value of the estimated existing losses (0.89 million af/yr at Lake Powell and 0.88 million af/yr at Lake Mead) and assuming FMF losses to be the sum of projected evaporation losses at Lake Mead (1.1 million af/yr) and losses from Lake Powell of 0.15 million af/yr, and rounding the difference of 0.55 million af/yr to 0.6 million af/yr. We can replicate the value of 0.3 million af/yr of saving by assuming that existing losses are 1.6 million af/yr and that losses under FMF would be 1.3 million af/yr.

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