Human Modification of the Geomorphically Unstable Salt River in Metropolitan Phoenix

Martin Roberge  
*Towson University*

In-stream gravel mining, massive bridge piers, and channelization have all contributed to the geomorphic instability of the Lower Salt River channel in Arizona. Dam closure, changing dam operating rules, and the frequent modification of the channel bed have decreased our ability to predict the Salt River hydrology. Engineering practice has adapted to this situation and to a public that is increasingly intolerant of service disruptions by constructing larger bridges and extending levees. Building these larger structures may be counterproductive; future construction should not constrict the channel and should re-establish a braided river to decrease the energy available to the system. **Key Words:** Arizona, fluvial geomorphology, human impacts, Salt River, urbanization.

**Introduction**

The city of Phoenix and the Lower Salt River, both located in central Arizona (Figure 1), compete with one another for space and materials. Phoenix alters the Salt River with its growing demand for water, land, river crossings, and construction materials. In turn, the river has altered the city, changing its course, scouring its bed, and repeatedly destroying bridges and structures along its banks. Bridge design, engineering practice, and management of the Lower Salt River have evolved against this background of rapid population growth and startling changes to the hydrology of the Salt River.

This investigation uses historical methods to review how planners and engineers around the Salt River have been forced to adapt to both changes in hydrology and changes in public opinion. Two related questions guide this research. First, how has the Salt River responded to increasing human modification of the river? Second, how has engineering practice adapted to these changes?

One pattern to emerge from this historical analysis is that human modifications to the Salt River have made the channel less stable and the hydrology more difficult to model or predict. Local governments have attempted to reduce the resulting uncertainty by completely re-engineering the Salt River through channelization and by dramatically increasing the size of bridge designs.

**Study Site**

**Description of Physical System**

The Salt River basin drains the southern rim of the Colorado Plateau and covers an area of 50,436 km² (19,473 mi²). The Lower Salt River, which starts at the Granite Reef Dam, east of Phoenix, divides the metropolitan area in half before joining with the Gila and Colorado Rivers. Since construction of a series of six dams upstream from Phoenix, the Salt River below Granite Reef Dam is a dry channel that receives water only during exceptional floods or from local storm runoff (Central Arizona Water Survey 1983; Figure 2). Infrequent high flows are typically contained within a 400-meter wide braided channel, while the occasional winter or spring low flows are conveyed in a meandering channel set into the larger braided flood channel. This compound channel form is typical of arid region and dammed rivers (Graf 1983, 1988a).

Floods along the Lower Salt River have had a history of being destructive, necessitating an array of flood-control structures that can be astonishing to visitors familiar only with the dry riverbed. In the past forty years, at least two structures have failed in each of the last five major floods over 1,900 cubic meters per second (cms; equivalent to 67,000 cubic feet per second, or cfs; see Table 1). Except for the most recent flood in 1993, there have been major transportation disruptions in each of the these five flood events, requiring bridge closure and...
replacement at all but three of the approximately fourteen bridge crossing sites in the Phoenix area. Figure 3 presents the lifespan of various crossings in diagrammatic form. Lines terminating in an “X” represent bridges destroyed by a flood.

**Figure 1** Metropolitan Phoenix and the Salt River. The Granite Reef Dam separates the Upper and Lower Salt River watershed. The Lower Salt River is dry in most years.

**Figure 2** Annual peak flow at Granite Reef Dam, 1891–2000. Discharges were measured at Priest Drive Bridge after 1994.
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River Development during the Hohokam and Territorial Periods

The Hohokam (850–1450 CE) made the earliest attempts to control the Salt River. Small diversion dams supplied several large towns and as much as 5500 ha of irrigated fields with water (Masse 1981). Although these dams supplied the largest prehistoric irrigation system in North America, they are unlikely to have disturbed the flow of the river. For this reason, the

Table 1  Damage in Phoenix Due to Salt River Flooding

<table>
<thead>
<tr>
<th>Date of Flood</th>
<th>Peak Discharge</th>
<th>Total Damage</th>
<th>Number of Open Bridges</th>
<th>Number of Closed Bridges</th>
<th>Cost of Travel Delays reported</th>
<th>calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1965</td>
<td>1,897 cms</td>
<td>31.8</td>
<td>3</td>
<td>not reported (17)b</td>
<td>1.7</td>
<td>—</td>
</tr>
<tr>
<td>March 1978</td>
<td>3,450 cms</td>
<td>63.6</td>
<td>2</td>
<td>9</td>
<td>1.1</td>
<td>11.36</td>
</tr>
<tr>
<td>December 1978</td>
<td>3,964 cms</td>
<td>103.0</td>
<td>2</td>
<td>10</td>
<td>31.7</td>
<td>20.73</td>
</tr>
<tr>
<td>February 1980</td>
<td>4,813 cms</td>
<td>103.7</td>
<td>2</td>
<td>10</td>
<td>17.6</td>
<td>17.85</td>
</tr>
<tr>
<td>January 1993</td>
<td>3,500 cms</td>
<td>not reportedc</td>
<td>18</td>
<td>3</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


a In millions of 2000 dollars, using annualized Consumer Price Index values to adjust reported values.
b Seventeen crossings were reported closed, including an unknown number of bridges.
c Calculated from lost work hours times $8.50 per hour (in millions of dollars).
d Not reported, but likely under 5 million dollars.

Figure 3 The lifespan of bridges along the Lower Salt River.
natural flood regime of the Salt River may have resembled the discharges during the Hohokam and territorial eras. Under these nearly natural conditions, flow through the arid Salt River could occur year-round, but was highly variable, with occasional dry reaches and sudden, massive, turbulent floods that prevented navigation (Littlefield 1996).

Settlement of the Phoenix area by U.S. citizens occurred after Arizona was made a territory in 1863. At the time of Arizona’s initial survey in 1868, the Salt River was a broad, braided channel lined with cottonwoods, willows, and occasional marshy land (Pierce and Engalls 1868). Soon after the survey, Anglo-Americans rebuilt ancient Hohokam dams and canals (Graf, Haschburger, and Lecce 1988, 81; Zarbin 1997).

The highly variable discharge of the Lower Salt River is capable of mobilizing the riverbed under flows of only 350 cms (12,300 cfs) (Parker 1992) to 700 cms (25,000 cfs) (Graf 1983), potentially undermining any channel structures. This constant threat forced the Hohokam and Anglo settlers to rebuild their dams and canals repeatedly (Huckleberry 1997), and was responsible for at least three early railway bridge collapses at the most secure bridge site (Figure 4), in 1888, 1891, and 1905 (Lykes 1993). In 1891, just before the end of this period of relatively unaltered hydrology, the largest discharge on record, a flood of 8,500 cms (300,000 cfs), ripped through the Salt River channel at Phoenix (Figure 5).

**Figure 4** The Santa Fe Rail Road at Tempe, Arizona, c. 1888. This bridge site is one of the most secure because it is one of the only sites in the valley where it is possible for the piers to reach bedrock. Courtesy Luhrs Family Collection, Arizona Collection, Arizona State University Libraries. CP LFPC 425.
south runway of Phoenix’s major airport, Sky Harbor, extended 850 meters (2600 feet) into the river channel (U.S. Army Corps of Engineers 1966). In Tempe, a sewage treatment plant and other structures occupied 50 percent of the width of the Salt River, and in 1969, dikes pinched the channel at one point down to a clearly inadequate 13-meter (40-foot) opening (Ruff 1971).

The 1978–1980 Floods

In March 1978, rainfall onto the snow pack in the upper Salt watershed produced a torrent of water that was unprecedented in the postdam period. Authorities closed all of the automobile bridges over the Salt River except for the Mill Avenue, Central Avenue, and Interstate 10 bridges (see Figure 6 for bridge locations). The flood caused 3.2 million dollars of damage to the south runway extension at Sky Harbor Airport, and damaged a parking lot at Arizona State University. The 16th Street Bridge was undermined by scour and then destroyed by the river. At the time, the 3,450-cms (122,000-cfs) flood was estimated to have a recurrence interval of slightly more than 40 years (U.S. Army Corps of Engineers 1979a).

In December 1978, winter rains again brought water to the dry urban reaches of the Salt River. In addition to the bridges that were still damaged from the earlier flood, two more bridges at 48th Street and 19th Avenue were damaged and later replaced with grade-level crossings, and I-10 was closed to traffic due to an undermined pier (U.S. Army Corps of Engineers 1979b). This round of closings effectively

### Table 2  History of Dam Closure along the Salt River and Tributaries

<table>
<thead>
<tr>
<th>Dam Name</th>
<th>Other Name</th>
<th>Year</th>
<th>Length*</th>
<th>Height*</th>
<th>Storageb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite Reef Dam</td>
<td></td>
<td>1908</td>
<td>344</td>
<td>9</td>
<td>0.9</td>
</tr>
<tr>
<td>Roosevelt Dam</td>
<td></td>
<td>1911</td>
<td>220</td>
<td>87</td>
<td>1,917.5</td>
</tr>
<tr>
<td>Roosevelt Extension</td>
<td></td>
<td>1996</td>
<td></td>
<td>+21</td>
<td></td>
</tr>
<tr>
<td>Mormon Flat Dam</td>
<td>Canyon Lake</td>
<td>1925</td>
<td>116</td>
<td>71</td>
<td>83.9</td>
</tr>
<tr>
<td>Horse Mesa Dam</td>
<td>Apache Lake</td>
<td>1927</td>
<td>201</td>
<td>94</td>
<td>322.2</td>
</tr>
<tr>
<td>Stewart Mountain Dam</td>
<td>Saguaro Lake</td>
<td>1930</td>
<td>384</td>
<td>65</td>
<td>87.6</td>
</tr>
<tr>
<td>Bartlett Dam</td>
<td></td>
<td>1939</td>
<td>244</td>
<td>87</td>
<td>219.7</td>
</tr>
<tr>
<td>Horseshoe Dam</td>
<td></td>
<td>1945</td>
<td>457</td>
<td>44</td>
<td>162.0</td>
</tr>
<tr>
<td>Orme Dam (proposed for flood control)</td>
<td>1983</td>
<td>1,737</td>
<td>59</td>
<td>2,034.5</td>
<td></td>
</tr>
</tbody>
</table>


* In meters.

b In millions of cubic meters.

c On the Verde River, a major tributary of the Salt River.

d Bureau of Reclamation (1976).
split the city in two, as thousands of workers were separated from their jobs by long commutes over the remaining bridges (Table 1).

The 4,000-cms (140,000-cfs) flow in December 1978 was followed a year later by a larger flood of 4,800 cms (170,000 cfs) in February 1980. This third flood crippled the city by wiping out twelve of the fifteen bridges over the Salt River, requiring major repairs or replacement in every case. Only three bridges remained open in 1980: the two-lane Mill Avenue Bridge, the Central Avenue Bridge, and the Southern Pacific Railroad Bridge. A fortunate turn of events allowed the I-10 bridge to reopen after a closure of only thirteen days, when a large scour hole was largely refilled during the waning stages of the flood. For the two weeks that the interstate was closed, Phoenix enjoyed a never-to-return vision of what a commuter rail system might look like, as the rail bridge was used to ferry commuters back and forth across the river for their jobs. The Central Avenue Bridge, built in 1975, probably survived after repairs because it was designed to withstand floods of up to 5,700 cms (200,000 cfs; U.S. Army Corps of Engineers 1981).

The bridge design process for the Lower Salt River transformed radically within weeks of the 1980 flood. A Governor’s Special Task Force made recommendations that the Salt River be channelized from McClintock Drive in Tempe to 40th Street in Phoenix, and that Roosevelt Dam be raised to provide flood protection (Flood Control District of Maricopa County 1994). Within a month of the 1980 flood, the Army Corps of Engineers revised the standard flood frequency estimates upward using a new method that included all of the floods on record, modified by a process model of how the flow would have been affected had the existing dams been in place. These methods transformed the 1980 flood from a 100-year flood to a 65-year flood (Figure 7; Leach 1980a).

Since 1980, construction in the Lower Salt River has proceeded at a rapid pace; however, most structures are now designed to withstand floods as large as the 1980 flood. The added costs associated with the larger structures have been covered by the 1978–1980 disaster assistance (Sowers 1980), and by a greater reliance on state and federal money.

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**Figure 6** Structures along the Lower Salt River. Channelized sections are indicated with a box. Refer to the legend to find the name of each bridge or crossing.
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Discussion

Aggressive versus Conservative Approaches to Development

Since the completion of Roosevelt Dam in 1911, there have been two opposing approaches to developing the once braided channel of the Lower Salt River. The more conservative of the two approaches has been to leave the former channel area undeveloped, or to at least design structures in the anticipation that not every flood will be contained upstream. This viewpoint was difficult to maintain in the face of the 1941–1965 no-flow period. The alternative approach has been to develop the bed of the Lower Salt River. This approach has been strengthened by the usefulness of the Salt River as a corridor through Phoenix and as a source of cheap, centrally located land. Power lines, highways, and airplane approach corridors all follow the riverbed. Other uses include gravel mines, sewage treatment plants, landfills, parking lots, government office buildings (including the Maricopa County Flood Control offices), and now the Tempe Town Lake, created in the riverbed using inflatable dams and a clay liner.

The Scottsdale Road Bridge, built in 1970, is a good example of the interplay between the conservative and aggressive development forces. This bridge typified the bridges designed at the time. It was designed to handle a flood of only 1133 cms (40,000 cfs) and had a bridge span of only 213 meters (650 feet). Like all of the bridges across the Salt River except for those near Mill Avenue, its footings were set into alluvial fill, since bedrock is too deep to reach at this site. To provide for large floods, a dip was built into the road approaching the bridge, allowing water to flow over the approach. However, by early 1978, Maricopa County had built low dikes across this dip in order to keep the bridge open as much as possible during high flows (Figure 8). This strategy disabled the bridge in 1978, when the dikes rerouted the two floods of 1978 (3,450 cms and 3,964 cms) through the span, thereby scouring a large hole to within a foot of the pier footings (Bridge Scour Committee 1979). In response, it was recommended that Maricopa County remove the dikes and double the length of the span. Before this could happen, another larger flood destroyed what remained of the bridge in 1980.

Bridge Design and Public Outrage

As in the Scottsdale Road example, the majority of bridges and river crossings built between 1945 and 1980 were intentionally designed to be small. During most years, culverts were sufficient to protect a road from any local runoff. Planners also reasoned that it made no sense to build a bridge that could withstand a 100-year flood when it would have to be replaced in 50 years to accommodate more traffic. A study commissioned by Phoenix after the first flood in 1978 balanced the potential costs of various sized bridges against the possibility that they

Figure 7 Two flood-frequency diagrams for the Lower Salt River. The black line indicates a flood-frequency diagram established in 1972; the gray line is the official flood-frequency curve released in 1980, after a major flood. Source: Central Arizona Water Survey (1983).

Figure 8 A schematic drawing of the Scottsdale Road Bridge shortly before its destruction in 1980. Note the dip section on the south end of the bridge. The dike was added later to prevent water from flowing through this section, and instead funneled the water under the span. Unfortunately, the span was designed for a discharge of only 1133 cms (40,000 cfs). Based on aerial photography taken 15 December 1979.
might be damaged in a flood (Advance Transportation Planning Team 1978; Figure 9). Despite the closure of all but three river crossings in the floods of 1965 and 1978 (U.S. Army Corps of Engineers 1966, 1979a) it was recommended that major river crossings still be designed to withstand floods with only a thirty-year recurrence interval (Advance Transportation Planning Team 1978).

The public disagreed with this strategy. Massive traffic delays at the two remaining auto crossings in December 1978 and February 1980 separated thousands of workers from their jobs and cost an estimated $20.4 million dollars in lost time ($49.3 million in 2000 dollars; U.S. Army Corps of Engineers 1979b, 1981; Table 1). The two-week traffic slowdown was not acceptable to the public; it was no consolation that the chance that it would happen again was less than 2 percent in any given year. Instead, once the public and elected officials understood the consequences of bridge failure, it seemed preferable to spend the extra money and to build monolithic bridges rather than face the traffic delays again. Robert C. Esterbrooks, the Maricopa County Engineer, recommended that longer bridge spans be used at river crossings, because he said he was tired of receiving criticism about damage to bridges that had deliberately been designed to withstand only smaller floods (Leach 1980b). In the immediate aftermath of the 1980 flood, several bridges in the planning phases were quickly redesigned to handle much larger floods of 5,700 cms (200,000 cfs) (Table 3). Although a flood of this size is roughly equivalent to the 1972 estimates of the 100-year flood, the new 1980 estimates placed the 100-year flood much higher (Central Arizona Water Survey 1983; Figure 7).

The 202 Viaduct, built in 1995, is an extreme example of the new design standards being applied to construction. This massive bridge has a span of 1.6 km, and is supported by 182 three-meter wide piles that extend 40 m below the surface. Construction of the 202 Viaduct cost $38 million dollars (Walsh, Schock, and Jimenez 1996).

The Lower Salt River Still Poses a Threat

The remaining destructive power of the Lower Salt River is surprising, considering the increasing number of control structures and the added ability to regulate the discharge of the Salt River. Uncertainty still confronts the design process along the Lower Salt River, notwithstanding the fact that we now have over a hundred years of experience in working with the river. Despite a history of attempts to control it, the Lower Salt River remains an uncontrolled river.

Why has our increased knowledge and ability to regulate the flow of the Salt River been unable to prevent the regular destruction of bridges and levees? In the following two sections, this article describes two possible explanations for this fact. First, the gravel mines, protective structures, and levees built in the Lower Salt River have had individual impacts on the flow of the river that have collectively destabilized the channel, allowing the river to move laterally and to scour its channel more deeply. Secondly, the proliferation of control structures along the Salt River has made the hydrology of the total system less predictable. The most common methods used to predict the future behavior of the river are based on previous behavior. These empirical methods are inappropriate in a system where constant modifications to the channel and human participation in the behavior of the system render the con-
CEPT of an “equilibrium” condition meaningless and the use of statistical averages misleading.

**Argument One: Development Has Decreased Channel Stability**

In-stream gravel mining, scour of the channel bed, and channelization all threaten the stability of the Lower Salt River. The gravel mines, channel structures, and levees in the Lower Salt River channel each affect the hydraulics of the river in ways that can increase erosion downstream. As development in the channel bed intensifies, structures are built closer to one another and start to affect each other. The resulting physical environment is more mobile and less stable than it was before. This instability makes the Lower Salt River a more difficult place to build a structure.

**In-Stream Gravel Mining**

In-stream gravel mining is a major threat to structures in the Salt (Li et al. 1989) and other rivers (Bull and Scott 1974; Kondolf and Swanson 1993; Kondolf 1994). River channels provide cheap, clean aggregate that is especially easy to remove in a dry channel such as the Salt River. Unfortunately, they also cause lateral channel migration (Mossa and McLean 1997). A report for the Arizona Department of Transportation (Bruesch 1980) linked the majority of damage to the I-10 bridge in 1978 and 1980 to an upstream mining pit owned by Tanner Industries, which had redirected the channel thalweg (the line of fastest water flow), causing it to flow out of alignment with the wall piers of the I-10 bridge. In-stream gravel mining can also cause areas upstream from the mining pit to degrade through headward erosion (Lee, Fu, and Song 1993). Figure 10 displays an example of headward migration caused in 1993 by a mining pit near the Alma School crossing.

Channel mines are regulated through a permitting system, but this system is not responsive enough to the concerns of bridge engineers. In the Tanner case, the Arizona Department of Transportation could do little about the mining occurring just upstream from the bridge right-of-way except to buy the mining rights to the property or to threaten Tanner Industries with a lawsuit (Bruesch 1980). Recently, the Maricopa County Department of Transportation was forced to buy the mining rights for the 1.1-kilometer (.7-mile) stretch of the river shown in Figure 10, which threatened the Alma School Crossing (Andrzej Wojakiewicz, Maricopa County Bridge Engineer, personal communication, 21 May 1999). Channel mines still pose a threat in the downtown reaches of the Salt River, where five pits are located along the channelized river sections between the I-10 and 16th Street crossings, with more mines located west of 19th Avenue. One gravel mine, located near 20th Street, had a pit in 1999 that appeared from the levee to be deeper than the channel. The levee at this site is susceptible to collapse due to piping, because the materials of the area are highly permeable, and the pit is separated from the channel by less than twenty meters.

**Channel Scour**

A second major threat to the stability of the Lower Salt River channel comes from increased scour. Scour is the process whereby sediment is removed from the channel and transported downstream, resulting in net erosion at a site. Only after the 1987 failure of the Schoharie Creek/New York State Thruway bridge did scour start receiving more national media and research attention, despite the fact that it had long been acknowledged to be the leading cause of bridge failure (Harrison 1991). Recently, scour at bridges has been highlighted.

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**Table 3** Salt River Bridge Design Revisions Following the 1980 Flood

<table>
<thead>
<tr>
<th>Name of Bridge</th>
<th>Original Price</th>
<th>Revised Price</th>
<th>Original Design Flood</th>
<th>Revised Design Flood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country Club&lt;sup&gt;b&lt;/sup&gt;</td>
<td>—</td>
<td>$5 million</td>
<td>3,700 cms</td>
<td>—</td>
</tr>
<tr>
<td>16th Street&lt;sup&gt;b&lt;/sup&gt;</td>
<td>—</td>
<td>$6.6 million</td>
<td>3,700 cms</td>
<td>5,700 cms</td>
</tr>
<tr>
<td>24th Street&lt;sup&gt;c&lt;/sup&gt;</td>
<td>$2 million</td>
<td>$3 million</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>19th Avenue&lt;sup&gt;b&lt;/sup&gt;</td>
<td>—</td>
<td>$5.2 million</td>
<td>3,700 cms</td>
<td>5,700 cms</td>
</tr>
</tbody>
</table>

<sup>a</sup> “Original” refers to design specifications from before the 1980 flood.

<sup>b</sup> Source: Sowers (1980).

<sup>c</sup> Source: Staff (1980)
by a major engineering society as one of the most important research agendas (American Society of Civil Engineers and the Committee on Hydraulic Engineering Research Advocacy 1996). Despite this attention, scour is still poorly understood (Hoffmans and Verheij 1997) and often receives only limited treatment in bridge design textbooks (e.g., Xanthakos 1994, 1995; Melaragno 1998).

Scour is difficult to study; the rising stages of a flood tend to excavate sediment, while the waning stages of a flood will often fill these holes in, minimizing the apparent extent of the scour. In-situ devices that measure scour in the Lower Salt River must survive bombardment by cobble-sized particles and water velocities estimated to reach up to 6 meters (18 feet) per second in narrow reaches during the 100-year flood (Michael Baker Consulting, Inc. 1997).

Scour can be classified into two categories, general and local (Figure 11). General scour is the removal of sediment over a broad area, while turbulent forces around a structure cause local scour (Hoffmans and Verhij 1997). General scour may result from faster flows associated with channelization, clear water downstream from dams that has more potential energy available to move sediment, and by a sediment shortage that causes water to pick up more local sources of sediment. Local scour may result at locations where water is forced to speed up as it squeezes through a narrow space, such as the water rerouted under the Scottsdale Road Bridge in 1978. Scour may also be increased when water is not aligned with a solid wall-type pier, increasing turbulence as the water flows around the leading edge of the pier (Figure 12). This process was responsible for much of the damage to the I-10 Bridge in 1978 and 1980 (Bruesch 1980).

A number of structural solutions exist for the protection of bridges from flood erosion. On the Salt River, these typically add an additional 50 percent to the cost of a bridge (Andrzej Wojakiewicz, Maricopa County Bridge Engineer, personal communication, 21 May 1999). Revetments or rip-rap are massive, loose objects that are too large for the river to mobilize and that prevent scour of piers and channel walls. Drop structures are low steps placed in the channel bed that prevent the lowering of the channel bed upstream from the structure. Unfortunately, once the water passes over the drop structure, it “drops” to a lower level, pick-
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Energy and increasing turbulence. Two doctors were drowned in the 1993 flood when they attempted to canoe over a low drop structure and were caught in a roll vortex (Waters 1993). This same turbulence can also contribute to downstream scour.

The Downstream Effects of Channelization

A final protective measure against scour is channelization, in which a smooth, straight channel is built using levees on each side of the channel. There are a couple of reasons for channelizing a river. First, the channel is less likely to move laterally due to the levees. Second, the smoother, straighter channel provides less resistance to flow, reducing scour from turbulence.

However, channelization also has some well-documented risks (Brookes 1988; Brookes and Gregory 1988; Goudie 2000, 215). The reduced friction in a channelized river results in faster flows. This is demonstrated in a model of the Lower Salt River (Figure 13), in which the average velocity of the flow tends to be higher in the channelized reach of the river, and the fastest flows occur under and downstream from bridges. Faster flows mean that the water can move more sediment, increasing general scour. The Rillito channel in Tucson has deepened significantly since its channelization (Graf 1984; Chang 1988, 379), and channelization of the Santa Rosa Wash south of Phoenix has led to widening and deepening of the wash (Rhoads 1990). Increased scour in the Lower Salt River would help to undermine bridge piers and could lead to bridge failure.

In the short term, faster flows within a channelized reach can lower the water depth for a given discharge. The city of Tempe used this principle to justify placing hotels and other buildings associated with the Rio Salado/Town Lake project adjacent to the newly channelized Salt River (CRSS Civil Engineers 1992). This occurred despite earlier studies based on scaled-down physical models of the river that indicated the levees might not survive the 100-year flood (Chen, Fiuzat, and Roberts 1985). Tempe's reliance on levees to lower the river's stage may be further called into question by re-

![Figure 12](image12.png)

**Figure 12** Local scour caused by nonalignment of flow. When the stream flow is shifted out of alignment with a wall pier, local scour can develop from turbulent eddies. Plan view.

![Figure 13](image13.png)

**Figure 13** A plot of water velocity as calculated by HEC-RAS for the Lower Salt River. Source: Michael Baker Consulting, Inc. (1997).
cent research that suggests that flood stages along extensively engineered humid-region rivers may have risen two to four meters for a given discharge over the past century (Criss and Shock 2001).

A number of difficulties exist with channelization. First, the Tempe example illustrates how a levee may encourage development by fostering a new sense of security. Levees are still susceptible to scour and failure. The levees protecting the Sky Harbor Airport failed during the floods of 1965, twice in 1978, and in 1980. In 1993, this same section of levee was undermined by a flow of only 3500 cms (12,400 cfs), causing $2.1 million dollars in damage. The second concern over channelization is that the decision to construct such a channel structure is self-reinforcing. Downstream from the levee system, the rapidly moving water will be transferred into a rougher, unprotected channel. This could produce increased erosion or lateral movement of the channel. One solution to either of these problems is to extend the levees further. In 1980 after the floods, the old I-10 bridge was threatened by the newly built levee system protecting Sky Harbor Airport—so the levee was extended (Roberts 1980). Similar arguments may soon be used to protect the area between the 101/202 interchange upstream of the Alma School Road crossing. Gravel mines threaten this area, which has a new highway built along the channel banks. Extending the levees this far would create a 24-km channelized reach. Los Angeles has already gone through this process of levee extension and has re-engineered the Los Angeles River into a simple concrete trough (Cooke 1984; Gumprecht 1999). Before extending its levees, Phoenix must decide if it too wants to transform its river into a storm drain.

**Argument Two: Development Has Decreased Our Ability to Predict the System**

Bridge design along any river depends upon construction of the “flood-frequency curve,” which estimates the size (discharge) and frequency of floods for a given section of a river. This will determine the size of the “design flood,” or the largest flood that a bridge should be expected to withstand. Once the size of the design flood is estimated, it is necessary to model the behavior of this imaginary flood. This will determine the depth and speed of the currents at the proposed bridge site, so that measures may be taken to protect the structure from scour.

The Lower Salt River is a difficult system to predict for two reasons. The first difficulty is that the discharge is controlled in part by the decisions of the dam operators and in part by natural processes. Second, behavior of a given flood is difficult to model due to constant modifications of the channel. The following paragraphs explain how these two issues translate into increased uncertainty in the minds of engineers as they design a bridge. This uncertainty can lead to designs that are accidentally too small, or to massive designs that negate all uncertainty.

**Establishing the Flood-Frequency Relationship**

Uncertainty confronts the bridge design team at the outset, when the team must determine the size of the design flood. Typically, the design flood is set to the same size as the 100-year flood, so that there is only a 1 percent chance that the design flood will be exceeded in any given year. However, the concept of a 100-year flood requires rethinking in a system where variations in dam operating rules or mistakes in dam operation can dramatically alter the size of a flood. Once the Salt River was dammed, lower discharges were expected through the urban reaches of the river, but the exact size of this effect could not be predicted using an empirical relationship until a new, postdam record of flooding could be collected. After the disastrous floods of 1978 and 1980, the Army Corps of Engineers revamped these empirical flood-frequency relationships by conducting a “what if” scenario. Using numeric process models, they estimated how the Salt River dams would have affected earlier floods and established a new flood-frequency relationship using the adjusted discharges. Unfortunately, it is difficult to assess the accuracy of the new model, since flows are so infrequent. In any case, both the old and the new flood frequency estimates (Figure 7) would predict more than the only three flows of over 1000 cms (35,000 cfs) that have occurred since 1980.

The predictive powers of flood-frequency diagrams and other empirical relationships suf-
fer further when applied to a system that has the ability to “learn.” While the data for a new, postdam record are being collected, dam operating procedures change as experience accrues and hydrologic models improve. During the 1980 floods, the Salt River Project (SRP), which operates the dams upstream from Phoenix, used a hydrologic model, HEC-5, to conduct 35 dam-release simulations (Salt River Project 1983), allowing them to select the optimal release schedule for that particular storm event. A statistical model cannot accurately portray such decision-making processes, because SRP presumably becomes better at optimizing the release schedule as the hydrologic models improve and as dam operators gain experience. Changes in dam operating procedures have meant that attempts to calculate flood recurrence intervals for the Salt River have not met with much success (Chin, Aldridge, and Longfield 1991, 71).

Process Models and the Lower Salt River

Process models are also faced with significant challenges in an urban/human-modified river system. HEC-RAS is a program commonly used to model the height of the 100-year flood during bridge design. However, frequent construction in the channel of the Lower Salt River means that the expensive topographic surveys used to create a model in HEC-RAS are out of date soon after they are completed. In fact, the use of HEC-RAS in the highly mobile Lower Salt River may be problematic at the onset of a flood, since this model assumes that the channel floor does not change during a flood event (Graf 1988b). The Lower Salt River is fraught with uncertainty because the initial boundary conditions for process models are outdated before they can be tested against an actual (and rare) channel discharge (Roberge 1999, 53).

The infrequency of flows in the Lower Salt River has made the uncertainty in this system apparent, and yet most other urban river systems experience human-induced changes that are too rapid and exceed the ability of the river to “equilibrate.” Human changes to rivers are cumulative, and do not allow a river to vary randomly around an equilibrium or average state. Despite these issues, concepts of equilibrium and “steady state” abound in models used throughout the United States.

Conclusions

The Competing Needs of Society

Societal and geomorphic forces interact with one another as they shape the Salt River. Demands for less-expensive bridges with shorter spans compete with the need to build larger structures to deal with increased uncertainty. It was not considered economical to build large bridges to prevent a rare two-week service disruption, so bridges were built to withstand only up to a 30-year flood (Figure 9 illustrates the reasoning behind this decision). In 1980, after thousands of workers were separated from their work for two weeks, planners began to value reliability more highly than economy. Trade-offs occur again when levees are built to meet the need for riverside land. Channelizing the river this way has increased the river's power and ability to threaten downstream structures. The ability to regulate larger flows using upstream dams has weakened the ability to predict the size and frequency of future downstream floods. In part, this may be linked to the competing demands placed on dams to provide both water supplies and flood control. In-stream gravel pits are needed for new construction, but threaten the channel’s stability near older structures. In the end, all of these competing demands originate in society—the river plays the role of mediator. In order to balance these competing demands ourselves, we must better understand how society and hydrologic systems interact with one another.

Implications for Modeling an Urban Environment

To support the growth of Phoenix, the Salt River has been modified upstream by dams, and downstream by the placement of structures and mining pits within the channel. In response to these changes, the river has become more geomorphically active and more difficult to predict. The hydrology of the Lower Salt River is controlled by natural variations and by human behavior, resulting in changes over time that cannot be modeled accurately using static empirical relationships. The constant addition of drop structures, rip-rap, or channel mines means that there are more changes to the channel bed than there are opportunities for the channel to respond. Process models made for this environment must make predictions be-
before they can be tested, and once tested will only remain valid until the next channel modification. Finally, turbulence initiated by new structures will produce scour around older structures that were not designed to anticipate these changes. These unintentional effects will become more common as the development of the riverbed becomes more intensive.

**Stability through River Engineering, or through River Planning?**

Engineering practice has evolved over the years to incorporate the changing conditions of the Lower Salt River. The mobile channel and unpredictable conditions have led to massive bridge designs padded with a large margin of error to withstand the increased uncertainty. Bridges have become monolithic, designed to withstand scour from repeated large floods. Attempts have also been made to reduce uncertainty by confining the Lower Salt River within levees. This practice is unlikely to succeed, because it encourages construction near the river, and because it will lead to increased erosion downstream from the levees. As the levees are extended to deal with each new threat, the river is transformed into a simple storm drain.

Pressure to develop the Salt River bed will not go away. Instead, it must be directed and planned in such a way that it is still possible to maintain control over the flow of the river. The natural variability of a desert river does not pose a problem for society until structures have been placed in harm’s way. In Phoenix, the cheapest strategy to prevent flood damage may be through a phased-in removal of structures placed too close to the channel.

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MARTIN C. ROBERGE is an Assistant Professor of Geography at Towson University, Towson, MD, 21252-0001. E-mail: mroberge@towson.edu. His research interests include fluvial geomorphology, GIS, and the human impact on hydrologic systems.