Debris flows and Grand Canyon habitats -- integrating the physical and biological to manage a changing system

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ABSTRACT

The ecosystem of the Grand Canyon has been drastically altered since the closure of Glen Canyon Dam in 1963. Specifically, the habitats created by the Colorado River and the tributary debris flows that enter it have changed as the flow regime of the river has shifted. Debris flows create habitat through the formation of fan-eddy complexes at the mainstem-tributary intersections. Sandbars, return-current channels, backwaters, marshes, and high-water zones are all affected by these intersections, and the flora and fauna that they support is dependent upon the sediment input from debris flows and the water released from Glen Canyon Dam. An in-depth understanding of the effects of current dam management on habitat creation, degradation, and maintenance is essential if we wish to successfully conserve and manage the Grand Canyon ecosystem. Managing a system as diverse and as historically altered as the Grand Canyon requires integrating all of its physical and biological components. Many habitats have been identified within the Grand Canyon—what remains is to gather as much information as possible about the physical features and the ecology of each so that judgments can be made about which ecosystem features are worth maintaining and the correct actions can be taken.

INTRODUCTION

The Colorado River provides important habitat for both humans and wildlife traveling through and living in the Grand Canyon, Arizona (Uhler 2002). The river's presence creates an abundance of different habitat types in the otherwise primarily xeric landscape surrounding the canyon. Especially important are the annual and ephemeral streams and sediment-rich debris flows from side-canyon tributaries, which create complex tributary-mouthbays or debris fans at their intersections with the mainstem river. Debris fans constrict the river at mainstem-tributary intersections by depositing sediments of varying sizes to create the riffles and rapids that lead to the formation of many aquatic and terrestrial riverine habitats (Griffiths and Webb 2004).

Historically, the ecosystems of the Colorado River through the Grand Canyon were dominated by a collection of native flora and fauna whose life histories were determined by the habitats in which they evolved and to which they are adapted (Uhler 2002). The pressure of evolving in a dynamic and variable ecosystem resulted in many species specializing on certain canyon resources and conditions (Stanford and Ward 2001). A high number of these species utilize the unique habitats created by debris flows at the mainstem-tributary interactions. This specialization has contributed to the high number of endemic species historically found in the Grand Canyon (Webb et al. 1999a). Today, the presence of numerous dams on the Colorado River impedes the river's natural course and alters its historic flow regime (Stanford and Ward 2001). Specifically, the Glen Canyon Dam above Lees Ferry affects the Colorado River's stretch that flows through the Grand Canyon. The Colorado River has changed from having highly variable, seasonally fluctuating flows of sediment-laden water to having controlled, diurnally fluctuating releases of cold, clear water (Webb et al. 1999a). The habitats created by debris flows have been dramatically altered by this change; debris flows now provide sediment to a clear river, and the lack of high flows from the dam has resulted in significantly less reworking of debris fans (Webb et al. 1999b). One goal of the 1996 controlled flood was to provide high enough flows to rejuvenate, restore, and rebuild some of these declining habitats (Collier et al. 1997).

In this paper I discuss some key habitats formed by the Colorado River and the debris flows that enter it. For each habitat I provide background information about formation, a pre-dam versus post-dam comparison of habitat features and their ecological significances, and an analysis of the effects of the 1996 and 2004 controlled floods in the Grand Canyon. In-depth understanding of the effects of current dam management on habitat creation, degradation, and maintenance is essential if we wish to successfully conserve and manage the Grand Canyon ecosystem.

DEBRIS FLOWS

Debris flows enter the Colorado River from side-canyon tributaries as muddy slurries that are composed of greater than 80 percent sediment by weight (Griffiths and Webb 2004). At the mainstem-tributary intersections, the clear waters of the Colorado River pick up sediment from these debris flows and move it downstream. The clear water released from the dam makes debris flows in the canyon an even more important source of sediment input than they were in the past. Historically, the Colorado River was brown with its heavy sediment loads. Therefore, its current clear, sediment-hungry waters easily pick up many particles deposited by debris flows (Booth 2005). Sediment that is too large or heavy to be moved downstream by the water levels released from Glen Canyon Dam forms debris fans at many of the mainstem-tributary intersections (Buer 2005) (Fig. 1). The result is a partial blockage of the river's course, which leads to the formation of a fan-eddy complex (Griffiths and Webb 2004).

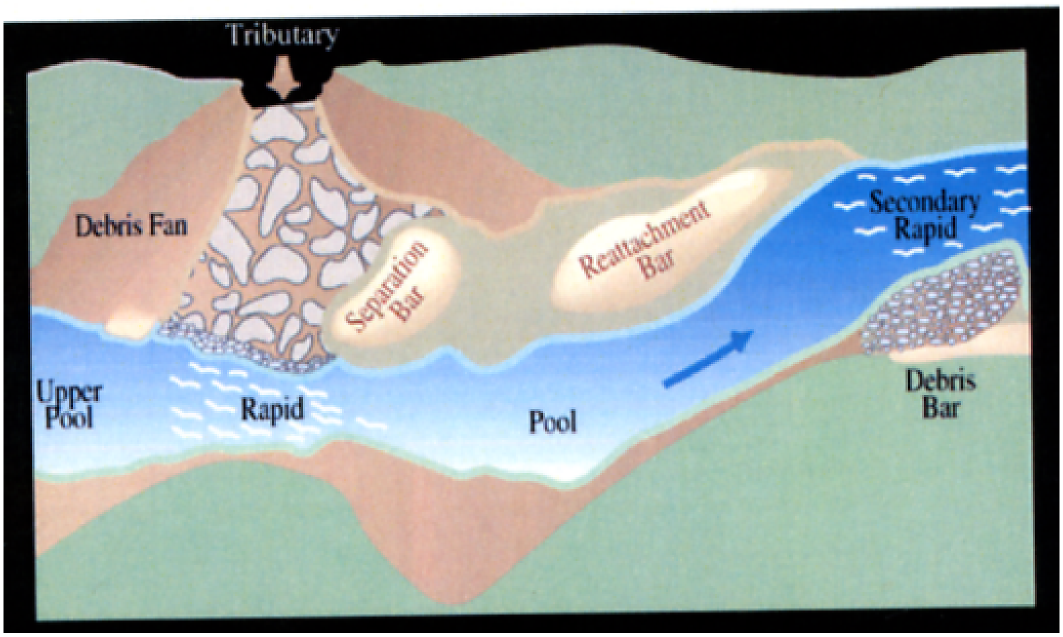

Figure 1. The structure of a debris fan at a mainstem-tributary intersection. Debris flows from side-canyon tributaries constrict the mainstem channel width, resulting in rapid formation. The resulting fan-eddy complex includes the debris fan, rapids, pools, sandbars, and backwater eddies. (Ref: Webb et al. 1989, USGS Prof. Paper 1492)

The fan-eddy complex is composed of the debris fan, and the rapids, pools, and sandbars that it creates (Dolan et al. 1978). When debris flows enter the river, large sediments such as boulders dam sections of the mainstem river. This damming creates rapids as the rushing water is forced to flow through a narrower and more obstacle-filled channel. The rapids, in turn, lead to the formation of upper and lower pools, where the water has slower velocities in the wider areas before and after the constricted sections (Griffiths and Webb 2004). This sudden change in current leads to the formation of eddies, where the water entering the post-rapid pool is forced to flow against the stagnant water behind the obstacle, resulting in a friction that leads to the creation of a cell of upstream flow. This upstream flow is often sharply divided from the river's normal downstream flow by an "eddy-fence," (Fig. 2) and is bordered by an upstream separation bar near the debris flow and a downstream reattachment bar after the post-rapid pool (Carothers and Brown 1991; Griffiths and Webb 2004).

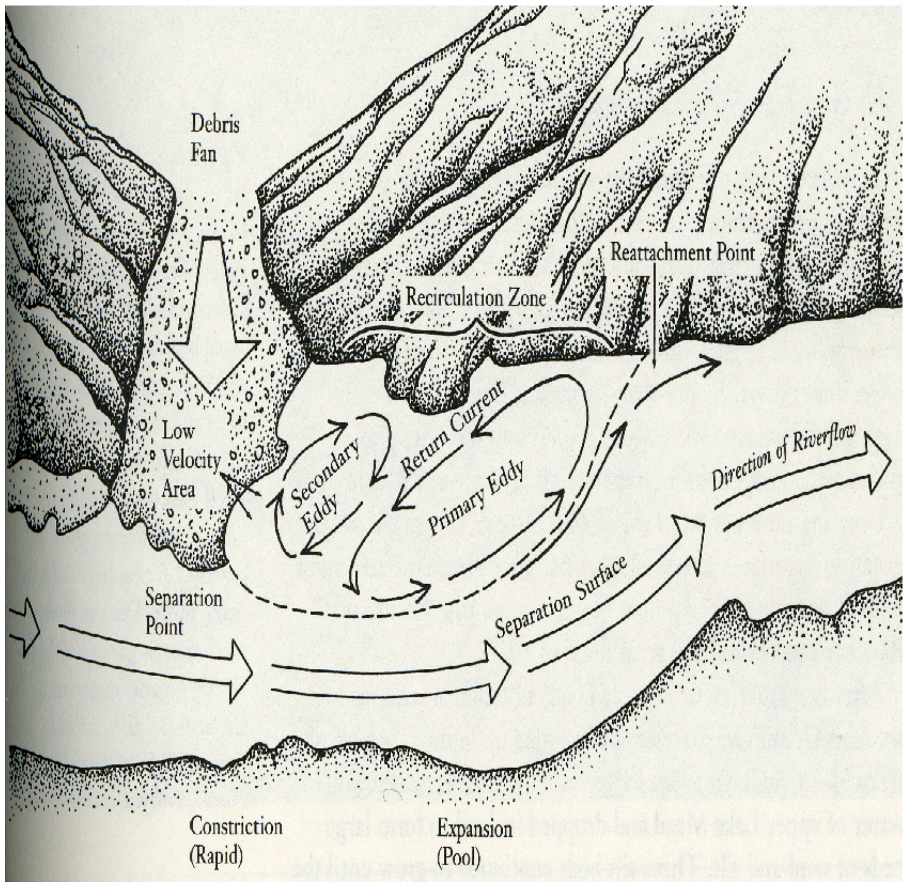

Figure 2. Recirculating eddies are separated from the mainstem river by an "eddy fence," depicted by the dashed line (Carothers and Brown 1991).

Habitats in and around the fan-eddy complexes include sandbars, return-current channels, backwaters, marshes, and high-water zones. Each debris fan's habitats have different physical characteristics based on the interaction between the frequency and magnitude of debris flows, and the frequency and magnitude of the mainstem high flows that rework debris deposits. Before the dam's closure in 1963, the Colorado River was defined by a daily and seasonally fluctuating environment. The river's hydrology included very large spring snowmelt floods, which provided the current necessary to rework debris fans to change rapids, and to form sandbars, return-current channels, and backwaters (Patten et al. 2001). The closure of the dam has essentially eliminated the occurrence of very high flows, which has severely limited the reworking of debris flows. Many habitats that debris flows create in and around fan-eddy complexes have therefore been affected by changes in the Colorado River's flow regime.

HABITATS

Fan-eddy complexes formed by debris flows create an array of habitats along the Colorado River corridor by providing a gradient of water depth and flow rate between the aquatic and terrestrial environments. A habitat is an area that has all of the potential resources necessary to support an organism, and that is actually used by the organism. Habitats offer resources such as food, water, and shelter to the flora and fauna that colonize them. Each habitat's physical characteristics, including substrate, age, water depth, etc., create a unique environment for the vegetation, fishes, mammals, birds, reptiles, amphibians, and invertebrates of the Grand Canyon. Sandbars, return-current channels, backwaters, marshes, and high-water zones, all exist at fan-eddy complexes, and provide important habitat for many Grand Canyon species. As conservationists focus on the preservation of the Grand Canyon, it is important to understand the physical characteristics and ecological significance of each of these habitats, to recognize how the dam has changed them, and to understand the effect that pulse flows will have on their creation and maintenance.

Sandbars

Formation

After debris flows come down the tributaries, sediment gets deposited into the mainstem of the Colorado River. Fine-grained sediment gets deposited in areas of very low velocity flows such as in eddies and at channel margins adjacent to wide, low-gradient reaches of the river (Stevens et al. 1995). Different current speeds above, through, and below the rapids created at debris fans create separation bars and reattachment bars as the river incorporates the smaller particles into its flow. The particles small enough to be moved by the flow are carried downstream, where they are often cast up onto the banks surrounding the circulating eddies in the fan-eddy complex (Fig. 3). Sediment is also deposited on the river bottom downstream of debris flows. High flows initiate circulation of sand off of the river bottom and deposit it at higher elevations, creating shoreline sandbars in some areas downstream of debris flows (Schmidt et al. 2000; Booth 2005; Buer 2005).

Figure 2. Morphology of Granite Rapid, a typical debris fan and rapid of the Colorado River in Grand Canyon. 1, tributary debris fan; 2, boulder-controlled rapid; 3, debris bar (island); 4, riffle or rapid caused by debris bar. (Photograph by the Bureau of Reclamation, 1967). The arrow indicates the direction of river flow.

Figure 3. Photograph and description of Granite Rapid. Numbers one through four indicate location of debris fan, rapid, debris bar, and riffle (Griffiths and Webb 2004).

<u>Physical characteristics</u>

Sandbars lie directly along the shoreline of the Colorado River. Three distinct types of sandbars have been defined based upon their location and their formation: separation bars, reattachment bars, and channel-margin deposits (Fig. 4). Separation bars occur on the downstream side of debris fans, directly upstream of the eddies formed by the widening channel exiting a more constricted rapid area. Reattachment bars form beneath the primary eddy, and extend downstream underneath this recirculation zone to surface in the slow-moving water near the downstream end of the eddy. Channel-margin deposits form when sand is compiled onto channel banks and other flow obstructions adjacent to or in the river (Schmidt et al. 2000).

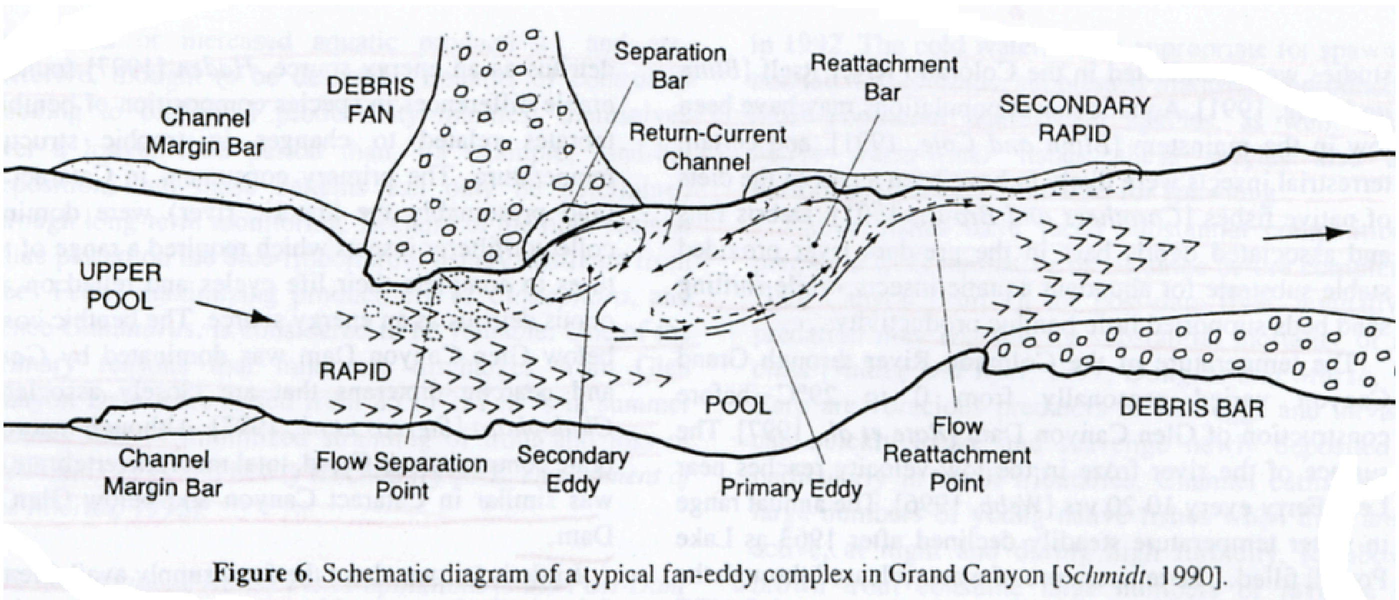

Figure 6. Schematic diagram of a typical fan-eddy complex in Grand Canyon [*Schmidt*, 1990].

Figure 4. Debris flows create separation bars, reattachment bars, and channel-margin debris bars (Webb et al. 1999a).

Ecological significance

Sandbars provide substrate for many types of riparian vegetation, which in turn provides habitat for a great diversity of species. The sandbar's proximity to water provides a relatively stable, hydrated substrate for riparian vegetation that does not occur anywhere else in the arid canyon (Infalt 2005; King 2005). Sandbars also provide valuable campsite "habitat" for river-runners when they are scoured clear by higher flows and kept free from encroaching vegetation. Sandbars make up the lowest elevation of the Grand Canyon terrestrial community. Heavily vegetated sandbars provide critical habitat for species of concern such as the Southwestern willow flycatcher *(Empidonax traillii extimus)* (Schmidt et al. 1998; Schell 2005). Sandbars also form essential aquatic habitats. Separation and reattachment bars border return-current channels, providing a barrier to flow in times of low current. This low flow results in the solar warming of these backwaters, which are crucial habitats for the early life phases of some native Grand Canyon fishes (Campos 2005).

Effect of Glen Canyon Dam

Before 1963, most sandbars were not heavily vegetated due to intermittent scouring by high flows through the canyon during times of increased runoff, such as the spring snow-melt (Infalt 2005). The dam's alteration of the Colorado River's natural flow regime has decreased its maximum flow levels, in turn severely limiting the scouring of the sandbars in the Grand

Canyon. Riparian vegetation typically found at higher elevations has initiated a gradual encroachment onto these sandbars, and complex vegetation communities now persist on many sandbars that have historically been barren (Webb et al. 1999a; Infalt 2005; King 2005). This new elevation level of the Grand Canyon's riparian vegetation communities has led to an increase in the diversity of wildlife present (Walters et al. 2000; Dettman 2005; Schell 2005). Many species have expanded their ranges into this new, lush riparian habitat. Lack of high flows has reduced the amount of debris flow reworking and sandbar rebuilding that took place under the pre-dam flow regime (Schmidt et al. 2000). The sandbars continue to shrink from erosion over time, and are no longer being replenished by the sediment-laden flows that used to occur in the canyon, primarily because virtually all of the Colorado's pre-dam sediment input is now being trapped behind dams upstream (Collier et al. 1997; Booth 2005). Beginning in 1974, significant sandbar erosion and serious vegetation encroachment were recorded; no significant rebuilding of sandbar size was noted, although the flood of 1983 appeared to scour some vegetation and temporarily redeposit sand onto some beaches (Webb et al. 1999a).

Effect of 1996 Flood

A major goal of the 1996 controlled flood was to rebuild the sandbars that had been gradually eroding since 1963 (Patten et al. 2001). The test flows of 1996 were high enough to carry and redeposit sediment from the Paria and Little Colorado Rivers and from debris flows throughout the canyon (Collier et al. 1997). For the first three to four days of the test flood, the river appeared to be casting its sediment up onto channel-margin bars in some areas, and to be scouring backwaters and reworking some debris fans enough to increase the overall surface area of separation and reattachment bars at the fan-eddy complexes (Collier et al. 1997). However, after day four of the seven-day flood, the river had begun to run out of sediment to transport, and the clear water flooding out of Glen Canyon Dam quickly eroded away at the newly deposited sandbars (Fig. 5) (Collier et al. 1997). The high flows also moved sand from some emergent sandbars surrounding return-current channels into the channels, making them shallower and beginning to fill in what would have historically been prime backwater habitat (Webb et al. 1999a). A high percentage of the newly deposited sand eroded quickly, but the overall surface area of sandbars did increase (Collier et al. 1997). These increases primarily took place along sandbars in fan-eddy complexes; channel-margin sandbars did not have a significant increase in surface area (Schmidt et al. 1998).

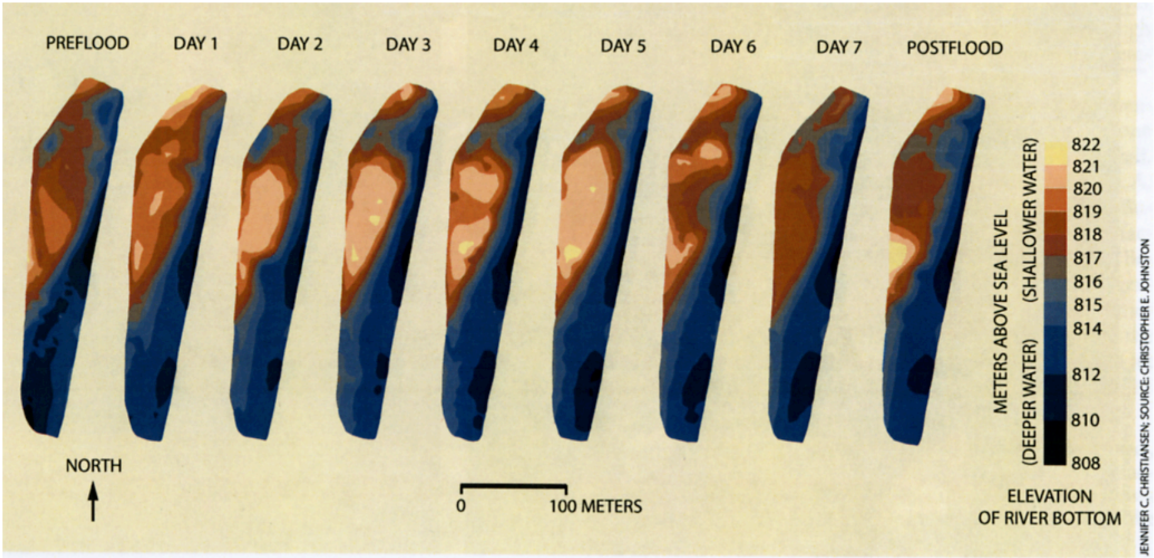

Figure 5. Deposition of sand within an eddy during the 1996 controlled flood. Until day five, the bed level was raised. After that, much of the newly deposited sand escaped back into the river (Collier et al. 1997).

Effect of 2004 Flood

The 2004 controlled flood was four days long, partly in order to limit the amount of erosion that would capture back any sediment deposited onto the beaches that they were trying to rebuild. The hope is that whatever sediment was redeposited onto sandbars will be less likely to immediately be washed away again. However, it seems unlikely that any significant increases made in sandbar surface area during the flood will be permanent, due to the current highly erosive flow regime (Booth 2005). Debris flows remain a major source of sediment to the Colorado River, though there are discrepancies about whether they provide enough sediment to maintain the historic habitat traits of sandbars (Booth 2005). Without high flows such as these controlled floods, the sediment and larger particles deposited by debris flows will never be reworked, so rebuilding of sandbars will be severely limited.

Return-current channels

Formation

During high flows return-current channels form in the recirculating eddies between the separation and reattachment bars of fan-eddy complexes created by debris flows. The water in these channels is pushed into the eddies as the river widens and is forced to flow alongside the stagnant water behind the obstacle causing the rapid; it then flows upstream along the riverbank until reaching the separation bar, where the cycle ends with this water merging again with the downstream-flowing mainstem (Stevens et al. 1995). As reattachment bars erode from fluctuating flows and wind, the mainstem river can further inundate these recirculation areas to form even deeper return-current channels with higher velocities (Brouder et al. 1999). However, sediment deposition into the return-current channels can eliminate them entirely, creating fluvial marshes in their place if they are not regularly scoured out by high flows. In times of low flow, the reattachment bar can become exposed, and the return current channel becomes fragmented, creating stagnant backwaters (Stevens et al. 1995).

Physical characteristics

Return-current channels only exist when flows are high enough to keep water flowing through them regularly. During low flows, the recirculating currents are partially cut off from the mainstem by the sandbars surrounding them. When this separation occurs, the return-current channels become low-velocity backwaters until degradation of the sandbars or high flows allow them to connect back to the mainstem river (Brouder et al. 1999).

Ecological significance

Return-current channels may provide a limited amount of shelter from the higher velocity and turbidity of the mainstem river (Webb et al. 1999a). These areas therefore may serve as refuges for some fish, although they do not provide as much shelter as the warmer, low velocity backwaters that exist during low flow conditions. Because they are partially discontinuous with the mainstem, return-current channels may be places of lower velocity flows when flooding occurs, or may provide escapes from any predators that are less inclined to cross the eddy-fence and leave the mainstem river. However, higher water clarity results from the lower turbidities of the return-current channels, so many fishes may be less likely to use them during daylight, thus avoiding increased visibility and greater predation risk.

Effect of Glen Canyon Dam

Glen Canyon Dam has had several conflicting effects on return-current channels. The overall lower flows released from the dam are often not high enough to completely reconnect the recirculation zones with the mainstem, so many return-current channels are left as backwater habitat instead. However, the lack of sediment in the post-dam river has resulted in a lack of rejuvenation of the constantly eroding sandbars (Collier et al. 1997). As the sandbars erode, lower flow levels are able to pass over the sandbars and into the recirculation zone. This increased inundation of the recirculation zone should result in the maintenance of more return-current channels, because the separated flow will more readily connect back to the mainstem river. Alternately, sediment eroded from these sandbars is often deposited into the recirculation zones, because the river's flow is not typically high enough to carry large sediment loads further downstream. This results in sediment deposition which decreases the depth of the recirculation zones and can lead to the formation of fluvial marsh habitat, because Glen Canyon Dam now prevents flows high enough to regularly scour out these areas (Stevens et al. 1995).

Effect of 1996 Flood

Sediment deposition from the 1996 test flood initially rebuilt sandbars, further separating recirculation zones from the mainstem and isolating them into what would become backwater habitats during normal lower flow. As the seven day flood continued, much of this newly deposited sand escaped back into the mainstem, leaving many eddies open to connect with the mainstem as return-current channels (Collier et al. 1997). The higher flows during the flood also scoured out sediment and vegetation that had filled in the backwaters during times of erosion and low flow, which opened up the recirculation zones to create more return-current channels and backwater habitats (Webb et al. 1999a).

Effect of 2004 Flood

According to the U.S. Fish and Wildlife Service's evaluation of proposals for future controlled flooding, a major goal is to rebuild sandbars (Spangle 2002). The shorter duration of this flood was supposed to deposit sand onto channel-margins and the sandbars of fan-eddy complexes without then recapturing this sediment back into the mainstem. An increase in the number or surface area of sandbars could lead to an increase in the flow levels necessary to turn backwaters into return-current channels. Alternately, the higher flows during the 2004 flood no doubt inundated many backwaters, at least temporarily scouring them out and turning them into return-current channels.

Backwaters

Formation

Backwaters are the pockets of low-velocity water found at the fan-eddy complexes when flows are low enough that the return-current channels essentially become stagnant toward the upstream end of the separation bars. When the Colorado River's flow is low, water rushing out of narrow rapids decreases its velocity as it expands to fill the wider area below rapids. When flow is low, return-current channels do not quickly rejoin the mainstream, and the isolated water stuck behind the sandbars becomes backwater habitat (Brouder et al. 1999).

Physical characteristics

Backwaters are bordered by a separation bar, a reattachment bar, an eddy fence, and the river shore. The lower velocity, shallower water remains relatively calm in the backwaters, allowing there to be higher temperatures here than the in the mainstem Colorado River. Backwater currents flow upstream in a very slowly recirculating eddy. These pockets of backwater habitat are clearly divided from the mainstem river by long separation bars, especially during times of low flows.

Ecological significance

Backwaters provide extremely important habitat for Grand Canyon fauna. Most notably, they serve as important rearing habitat for the juvenile life stages of many native and nonnative fishes (Schmidt et al. 1998; Campos 2005; Wilson 2005). A prime example of a native fish that utilizes the backwaters' low velocity flows and higher temperatures is the endangered humpback chub *(Gila cypha),* which relies on backwaters to shelter it from many threats of the mainstem river (Campos 2005). Abundances of adult humpback chub are found in channel reaches that contain numerous debris fans, showing the importance that debris flows can have on habitat creation and selection (Webb et al. 1999a). The young-of-year and juvenile humpback chub preferentially feed and mature in warm, near-stagnant backwater habitats (Webb et al. 1999a; Campos 2005). Slow water velocities in backwaters allow solar radiation to increase the backwater temperatures to be higher than the mainstream, which has become too cold for many native fish such as the humpback chub since the closing of Glen Canyon Dam (Webb et al. 1999a; Booth 2005; Campos 2005). These thermal refugia are home to high primary and secondary productivity, and therefore also attract fish looking for food (Webb et al. 1999a). Fluctuations in river flow can dramatically change the structure of backwater habitats. Very low flows can isolate these habitat pockets from the mainstem completely, and very high flows can both reconnect the backwaters, and scour out and deposit sediment into the scour holes until the backwaters are filled in (Webb et al., 1999a). Because of their extreme ecological significance, it is very important to understand how the management of dam releases will affect these habitats.

Effect of Glen Canyon Dam

Cold, clear water released from Glen Canyon Dam is unnatural and unsuitable for many native wildlife species. Therefore, backwater habitats are even more important today than they were in the past. The warmer backwaters now provide the only thermally suitable mainstem temperatures for some juvenile fishes (Schmidt et al. 1998). Historically, primary productivity of these backwaters was not as high as it is today, because there were high flow events to rescour the backwater circulation zones. With flow restrictions imposed by the dam, the backwaters are no longer regularly cleared out by high flow events, and vegetation communities within and around the backwaters have increased (Kearsley and Ayers 1999). In this sense, Glen Canyon Dam has increased the quality of backwater habitats by creating new, flourishing communities that provide food for higher trophic levels (Webb et al. 1999a). However, the clear water releases that allow this increased photosynthesis to take place also make the water more transparent for predators (Webb et al. 1999a; Purdy 2005). For this reason, some species now utilize these critical backwater habitats only transiently or during periods of high turbidity to decrease the risk of predation (Webb et al. 1999a). Another effect of Glen Canyon Dam has been the filling in of some backwaters. Periods of high sediment input (debris flows) and low fluctuating flows (constant low flow releases from dam) can result in backwaters becoming shallower as sediment is deposited into them (Webb et al. 1999b). Sediment deposition from debris flows and from the erosive flow regime that is gradually degrading the existing sandbars can fill in backwaters to the point that they are capable of supporting vegetation (Stevens et al. 1995). When this occurs, critical backwater habitat has been lost, and cannot be regenerated except by the occurrence of high pulse flows to scour out these now vegetated marsh areas (Webb et al. 1999a).

Effect of 1996 Flood

Because backwaters are essential habitat for so many native species, they should be a primary focus of conservation efforts. One goal of the 1996 controlled flood was to rebuild sandbars, which in turn would rejuvenate backwater habitats and hopefully help to restore struggling native fish populations (Schmidt et al. 1998; Campos 2005). The number of backwaters present in the Grand Canyon increased immediately following the 1996 flood (Fig. 6) (Brouder et al 1999).

This increase shows that at least in the short-term, pulse flows are capable of scouring out filled-in backwaters and of regenerating sandbars to create new backwater habitats (Collier et al. 1997).

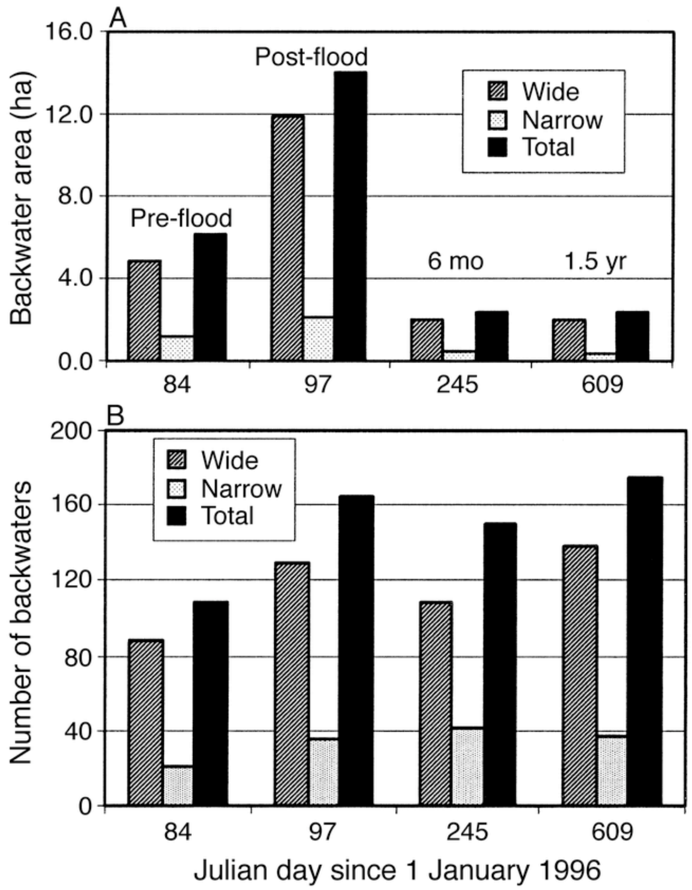

Figure 6. Number and area of backwaters pre-flood and at different times after flood (Schmidt et al. 2000)

<u>Effect of 2004 Flood</u>

Without the continuation of pulse flows to redistribute debris fan sediment to sandbars and scour outmarshes, backwater habitats will decrease due to erosion, especially if the current erosive flow regime of diurnally fluctuating flows is continued. In order to maintain current backwater habitats, consistent maintenance high flows must be done to slow the erosion of sandbars and to restrict the encroachment of marsh vegetation into the backwaters. The 2004 controlled flood was timed to coincide with high sediment loads coming into the mainstem of the river from the Paria and Little Colorado Rivers (Spangle 2002). Potential increases in sandbar numbers and surface area should increase the availability of backwater habitats as well.

Marsh

Formation

In the pre-dam Grand Canyon, marshes only occurred where perennial springs discharged into or near the mainstem channel or its tributaries (Webb et al. 1999a). These springs created moist areas with relatively lush, dense riparian vegetation not present elsewhere in the canyon's semiarid climate (Webb et al. 1999a). The closure of Glen Canyon Dam led to an increase in the number of marsh habitats in the Grand Canyon (Stevens et al. 1995). Debris flows from side canyons form fan-eddy complexes, which make up the sandbar and backwater habitats described above. Without high flows to scour out the eddies, erosion of the sandbars bordering backwaters is slowly filling in the slow-moving recirculation zones (Webb et al. 1999b). As the backwaters get increasingly shallow, vegetation is able to take root in the collecting sediment, and marsh habitat is created (Fig. 7) (Stevens et al. 1995). This marsh vegetation impedes return-current flows even more, thereby creating a self-perpetuating cycle of low velocity flows, increased sediment deposition, and vegetation encroachment (Infalt 2005; King 2005).

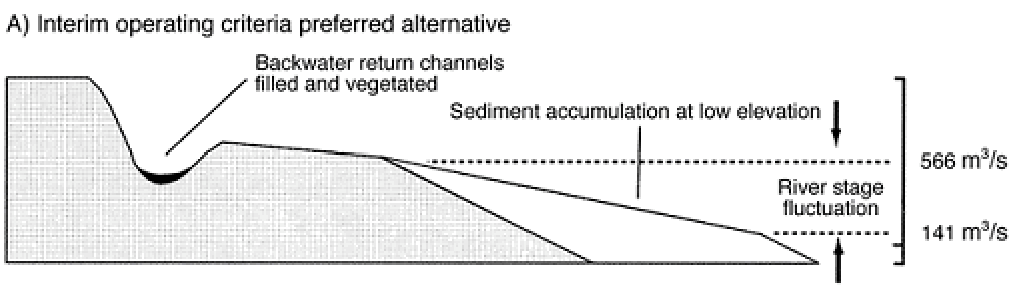

Figure 7. In the current flow regime, backwater return channels can be filled in by eroding sandbars and vegetated. The dark area shown in this picture is a possible marsh location (Schmidt et al. 2000).

Physical characteristics

Fine-grained eddy deposits are substrate for marsh vegetation (Stevens et al. 1995). The fine sediment deposited by debris flows is redistributed into sandbars of the fan-eddy complexes, and marsh vegetation is most commonly found on the reattachment bars of these when high flows do not scour the sandbars (Stevens et al. 1995). Marsh vegetation occurs in the interstitial zone between the low and high-water lines of the Colorado River, and also slightly above the high-water line (Infalt 2005; King 2005).

<u>Ecological significance</u>

The abundance of new fluvial marshes developing throughout the Grand Canyon has increased the diversity, production and habitat availability of these shoreline areas (Stevens et al. 1995). Riparian vegetation that normally was present only in small abundances high above the river's average flow level is now lining the riverbanks and filling the eddies, creating habitat for native and nonnative plants and animals. Shoreline marshes have been suggested as potential habitats for the endangered Kanab ambersnail *(Oxyloma haydeni kanabensis)*, which utilizes the monkey flower *(Mimulus cardinalis)* that can grow in filled in eddies along the Colorado River (Schmidt et al. 1998). However, the substrate of these marshes is very different than the rock in Vasey's Paradise on which this snail naturally occurs, so marsh habitat may not necessarily be an important conservation factor for this species (Purdy 2005).

<u>Effect of Glen Canyon Dam</u>

The generation of shoreline marshes is a post-dam phenomenon. Historically, high flows came through to scour out eddies and bury any encroaching vegetation (Schmidt et al. 1998). With high flows now absent from the Colorado River's flow regime, marshy riparian vegetation has been able to establish itself in the increasingly shallow backwaters as they are filled in by erosion. The closure of Glen Canyon Dam has therefore led to a direct increase in the species abundances and diversities of these areas (Stevens et al. 1995). These relatively new marsh habitats are the most productive habitats in the Grand Canyon (Schmidt et al. 1998).

<u>Effect of 1996 Flood</u>

The 1996 flood was successful in increasing sandbars and rejuventating backwater habitats. Marsh habitats should therefore have decreased, because backwaters and shoreline marshes are mutually exclusive within each fan-eddy complex. Marsh vegetation cannot survive through long periods of inundation, and it is scoured off of reattachment bars by high flows (Webb et al. 1999a; King 2005). This was demonstrated in the flood of 1983, which scoured an estimated 85 percent of marshes (Stevens et al. 1995). The high flows of 1996 wiped out or buried marsh vegetation in some areas, thus rejuvenating backwater habitats (Schmidt et al. 1998). The completion of the goal to rejuvenate backwater habitats was not a total accomplished, however, because conflicting interests working to conserve potential habitat for the endangered Kanab ambersnail took measures to save the same marshes that the high flows were meant to scour away. Before the 1996 flood, individual snails and monkey flowers were removed from the inundation zone, and then replaced after the seven day flood to reestablish their populations (Collier et al. 1997; Purdy 2005). Marsh habitat was therefore decreased overall during the 1996 flood, but partially replaced immediately afterward.

Effect of 2004 Flood

The 2004 controlled flood should have decreased availability of marsh habitat by scouring out backwaters in many areas and by redistributing sand to cover vegetation encroaching onto sandbars. The shorter length of this flood may have allowed some marsh vegetation to persist through the high flows—the length of time before marsh vegetation regenerates should be carefully watched and compared to the regeneration time after the 1996 flood (Infalt 2005; King 2005). As in 1996, measures were undertaken to conserve the Kanab ambersnail. This time, entire chunks of marsh vegetation sod (especially monkey flower) were cut out of the ground and placed on palates above the inundation zone so that they could be replaced and reestablished after the flood (Purdy 2005).

High-water zone

Formation

The high-water zone is the area along riverbanks reached when flow is at its highest point. The old high-water zone was high above the shoreline sandbars that make up the high-water zone today (Schmidt et al. 1998; Infalt 2005). As debris flows continue to enter the Colorado River without being reworked by high flows, large debris fans build up and allow vegetation to establish itself all the way down to the water line. The lack of high flows to scour off encroaching vegetation also has resulted in a much lower elevation high-water zone than the one that existed pre-dam

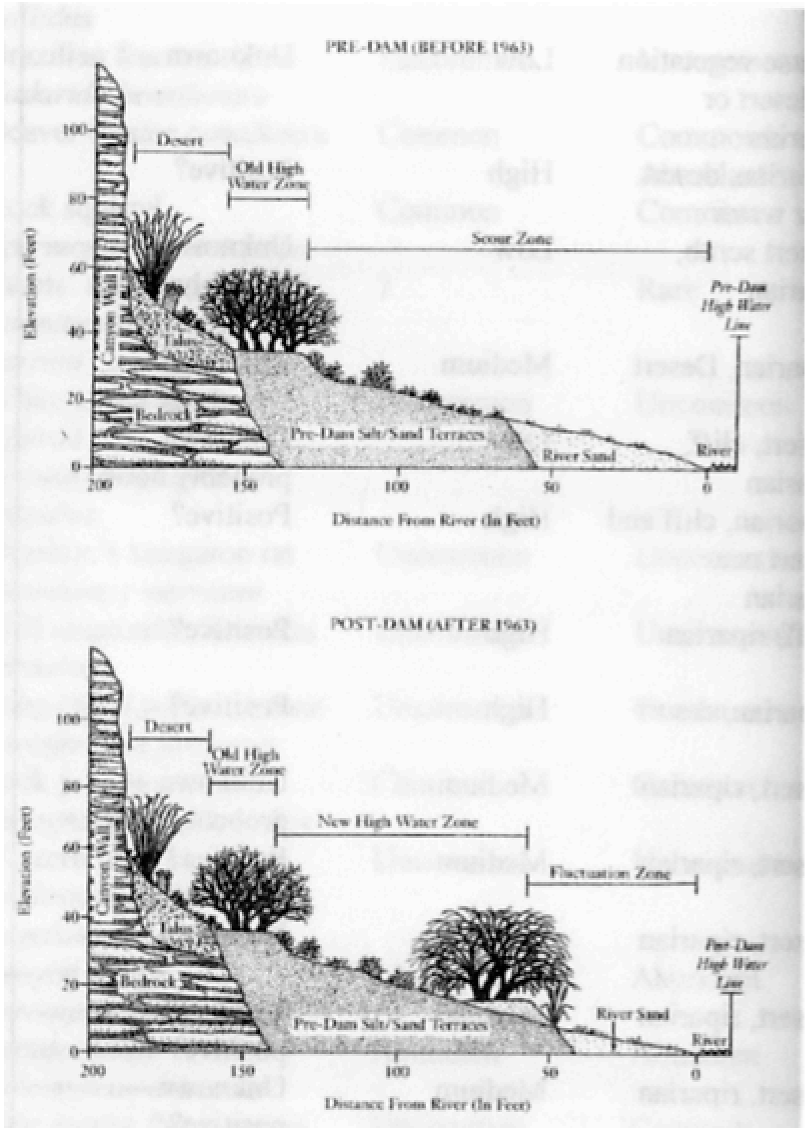

Figure 8. Comparison of pre-dam and post-dam high water lines and vegetation along different shoreline elevations (Carothers and Brown 1991).

Physical characteristics

The high-water zone historically was a distinct line below which vegetation could not persist. Today, this line is less distinct due to the existence of marshes and vegetated shorelines. Vegetation along the old high-water zone has decreased since the closure of Glen Canyon Dam, and a new, lower-elevation high-water zone has been established (Schmidt et al. 1998; Infalt 2005; King 2005). The old high-water zone is habitat for pre-dam perennial riparian vegetation (Schmidt et al. 1998; Infalt 2005). The new high-water zone is highly productive, and is habitat for a wide variety of native and nonnative plants that have flourished under the post-dam flow regime (Schmidt et al. 1998; King 2005). Salt-cedar *(Tamarix ramosissima)* is one of the dominant plants occupying this new high-water zone (Kearsley and Ayers 1999; King 2005).

Ecological significance

The change in vegetation communities along the new high-water zone has created new habitat for many wildlife species (Webb et al. 1999a). Lush riparian vegetation was not historically present throughout the Grand Canyon, and its presence has dramatically increased species diversity and abundances along this length of the Colorado River. Native and nonnative vegetation now covers sandbars that used to be regularly scoured by high flows, and native and nonnative wildlife have expanded their ranges to utilize this new habitat (Schmidt et al. 1998). For example, this new low riparian vegetation provides habitat for the endangered Southwestern willow flycatcher *(Empidonax traillii extimus)*, which nests and breeds in tamarisk (Schmidt et al. 1998; Schell 2005). Tamarisk was not common in the Grand Canyon prior to 1963, and its proliferation since then may have allowed the flycatchers to expand their ranges (Webb et al. 1999a; King 2005; Schell 2005). Vegetation communities that persist along the old high-water zone are composed of species that have so far been able to tolerate the drought conditions imposed on them by the closure of Glen Canyon Dam (Webb et al. 1999a; Infalt 2005).

Effect of Glen Canyon Dam

The closure of Glen Canyon Dam has created vegetation communities that exist at and below the new high-water zone, and has restricted the persistence of species along the old high-water zone. The old high-water zone is now never reached by the waters of the Colorado River, so the vegetation species that persist are those that can survive the drought-like conditions solely by utilizing rainfall (Webb et al. 1999a; Infalt 2005). Other species, such as some mature mesquite trees, have started to die off. Many species that are still able to persist at the old high-water line now have significantly lower recruitment (Collier et al. 1997; Webb et al. 1999a). The elevation of the new high-water zone is directly determined by the amount of water released from Glen Canyon Dam. Native and nonnative species are expected to continue expanding into the new lower riparian habitats as the old high-water zone becomes more fragmented and increasingly xeric (Carothers and Brown 1991; Infalt 2005; King 2005). The new high-water zone is diverse, with many native and nonnative plants (though tamarisk is dominant), five to ten times the number of breeding birds thought to have been present in the old high-water zone, and over 1200 acres (>500 ha) of new riparian habitat (Webb et al. 1999a). The new, lush riparian habitats through the Grand Canyon rapidly increased their total cover area in the new high-water zone, and continued to slowly increase cover in the old high-water zone as well (Webb et al. 1999a). As the vegetation in the new high-water zone increased in density, the rate of invasion into this new zone gradually slowed down, leaving the early-invading tamarisk as the dominant species in the new high-water zone (Webb et al. 1999a). This has a significant effect on the near-shore aquatic habitats (such as sandbars, return-current channels, backwaters, and marshes formed at fan-eddy complexes), because tamarisk makes its local environment more saline, and therefore less productive (Webb et al. 1999a). This indirect effect of Glen Canyon Dam contrasts with the increased productivity that has been observed due to the increased photosynthesis that has occurred in response to the dam's clear-water releases (Purdy 2005).

Effect of 1996 Flood

A primary goal of the experimental beach and habitat-building flood was to scour away large amounts of vegetation from the new high-water zone (Schmidt et al. 1998). The increased flow levels did inundate many vegetated sandbars, scouring away some of the new high-water zone habitat (King 2005). Some vegetation that was not scoured away was buried by the test flood's sediments, resulting in increased releases of many nutrients into the root zones of the scoured sandbars (Stevens et. al. 2001; Purdy 2005).

Effect of 2004 Flood

The 2004 test flood was also designed to rebuild beach and sandbar habitats. High flows carrying sediment down the canyon scoured away the lowest riparian vegetation zones, and deposited sand at higher levels, resulting in the burial of autochthonous and allochthonous vegetation (Purdy 2005). The effects of the nutrient influx that occurs after these burials need to be researched, and the sandbars need to be monitored to determine how long it takes for vegetation to reestablish itself on the newly scoured areas.

CONCLUSIONS AND RECOMMENDATIONS

The Colorado River is no longer a natural watershed. Management upstream, downstream, and through the Grand Canyon has altered the hydrology and ecology of this ecosystem by changing the habitat resources available. Understanding habitat change is essential if we wish to continue to manage or restore this system. To thoroughly understand habitat formation, change, and significance, we must integrate our knowledge of the physical and biological components of this ecosystem.

Sandbars, return-current channels, backwaters, marshes, and the new high-water zone are all important habitats that are directly affected by the management of Glen Canyon Dam. Each of these habitats supports its own group of wildlife, and value decisions must be made if we continue to try and prioritize one habitat's conservation over the others'.

All habitats are valuable for different aspects of the Grand Canyon ecosystem. However, they cannot all be promoted—rejuvenating backwaters will inherently destroy new marsh habitat, and vice versa. I believe that more, higher intensity experimental floods should be released from Glen Canyon Dam in order to see how if the habitats of this ecosystem will become somewhat self-sustaining. For example, if higher test floods are released (with flows high enough that marsh habitat could be destroyed), then we will have solid evidence of what sorts of flows marshes and the wildlife they support can actually withstand. From there, we can make better-informed decisions about whether newly created habitat such as marshes, etc., are indeed worth conserving (and we will be able to enumerate reasons why or why not).

To effectively manage Grand Canyon habitats, we must make thoughtful, but not overly cautious, decisions. If we do not test various flow regimes to understand the full range of our options, we will be attempting to manage without enough information or the correct tools. Alterations to the Colorado River so far have drastically changed the habitats available along the Colorado River. Therefore, I am in favor of continuing with tests to determine what our choices are. Only once we have gathered as much information as possible will we effectively be able to determine what hope we have of maintaining or restoring this ecosystem, and to decide how best to manage it.

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