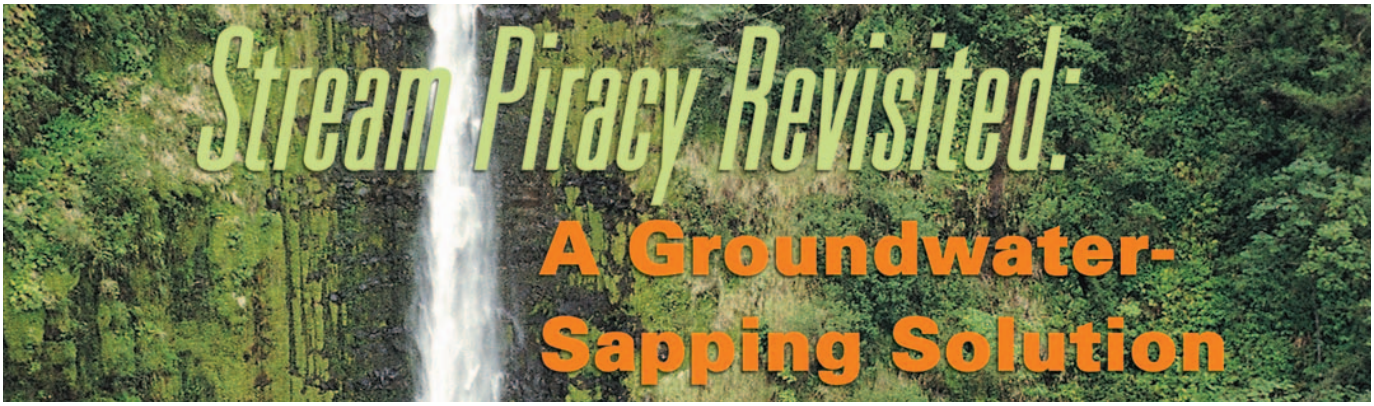

Stream Piracy Revisited: A Groundwater-Sapping Solution

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ABSTRACT

Stream piracy describes a water-diversion event during which water from one stream is captured by another stream with a lower base level. Its past occurrence is recognized by unusual patterns of drainage, changes in accumulating sediment, and cyclic patterns of sediment deposition. Stream piracy has been reported on all time and size scales, but its mechanisms are controversial. Some researchers conclude that stream piracy is a rare event and happens only on small scales; this is based on a recognition that surface-water energy decreases near divides and the belief that groundwater-sapping processes decrease in effectiveness near divides and are not effective in rock and cohesive sediment. In contrast, numerous studies show that groundwater-sapping is effective in rock and cohesive sediment, focused by the intersection of the extending channel with the water table, and effective in hillslope processes. Further, destruction of evidence by surface water is the reason for the general lack of recognition of groundwater-sapping effects. I argue that the persistence of groundwater-flow systems, coupled with the evolving geometry as a pirating stream approaches a divide, can sustain breaching by groundwater-sapping processes. The principal determinant of the maintenance of energy is the position of the groundwater divide as compared to the topographic divide where streams in adjacent drainage basins are at different elevations. Wetter climatic periods can add energy to the system as increased recharge causes groundwater levels to rise, accelerating stream piracy.

INTRODUCTION

The term stream piracy brings to mind an action of forcible taking, leaving the helpless and plundered river poorer for the experience—a takeoff on stories of the pirates of old. In an ironic sense, two schools of thought are claiming villain status. Lane (1899) thought the term too violent and sudden, and he used "stream capture" to describe a groundwater-sapping–driven event, which he envisioned to be less dramatic and to be the common mechanism for stream piracy. Crosby (1937) took issue with Lane (1899 and later papers) and argued that surface water is the principal agent of stream piracy in most settings. This set up a debate on the relative roles of surface-water erosion and groundwater-sapping erosion that persists today. This paper contends that groundwater-flow patterns and groundwater-sapping processes are important in most cases of stream piracy, and the final act of piracy can be rapid because of the developing geometry. There is a predictable imprint of groundwater flow, and groundwater sapping is effective at all scales and in all geologic material.

The issue of stream piracy is more than an academic discussion because it is an important geologic process—past and present. Sediment-deposition patterns and mineralogy can be drastically altered with the event of stream piracy. Stream piracy can change migration patterns for aquatic animals and can change rates of erosion in upland areas. Stream chemistry can be changed as a consequence of stream piracy. In some geologic settings, such as in a delta, stream piracy is a cyclic event. The final act of stream piracy is likely a rapid event that should be reflected as such in the geologic record. Understanding the mechanisms for stream piracy can lead to better understanding of the geologic record.

Recognition that stream piracy has occurred in the past is commonly based on observations such as barbed tributaries, dry valleys, beheaded streams, and elbows of capture. A marked change of composition of accumulating sediment in deltas, sedimentary basins, terraces, and/or biotic distributions also may signify upstream piracy (Bishop, 1995; Pissart et al., 1997; Mather et al., 2000; Johnsson, 1999). Recognition that piracy is happening now is based on observed higher erosion rates for streams with steeper gradients on one side of a drainage divide relative to the other, with the steeper gradient stream capturing the headwaters of the lower gradient stream (Bates, 1961; Vogt, 1991; Ries et al., 1998). As variants, development of karst aquifers can lead to underground capture of rivers over time, such as the recognition of loss of upper Danube flows (Hötzl, 1996), and cyclic development of lobes on the Holocene Mississippi River delta is modulated by stream capture (Roberts, 1997).

While the identity of the villain (mechanism) remains controversial, there are common elements in stream piracy regardless of the erosion process. To have energy to do the work of erosion and transport, the pirating stream needs to be at a lower elevation or have a steeper gradient. In addition, the geologic material near where the capture takes place must be susceptible to disaggregation by mechanical or chemical processes or to solution, or must already be disaggregated. The process of erosion at the channel head coupled with the geologic setting and energy in the system determines the rate and direction of channel extension. There must be a mechanism for transport of eroded sediment from the channel head. Bishop (1995) argued that in most settings, there is minimal energy for stream piracy and therefore little piracy. This paper will show that the evolving groundwater-flow system as a pirating stream approaches the divide can provide the threshold energy for breaching.

GROUNDWATER AND STREAM PIRACY

The phenomenon of groundwater "sapping" has been identified with a number of terms. Higgins (1984) expanded the term "seepage erosion" to encompass the more complex erosion of consolidated rock. He included intensified chemical weathering; leaching and dissolution within the seepage zone; and enhanced physical weathering by granular disintegration or flaking owing to wetting-drying, salt-crystal wedging, root wedging, rainbeat, congelifraction, and needle-ice wedging. Howard (1988a) further expanded the overall concept proposing "Groundwater sapping, as distinct from piping, is a generic term for weathering and erosion of soils and rock by emerging groundwater, at least partially involving intergranular flow (as opposed to the channelized throughflow involved in piping)" (p. 3). Groundwater sapping is used in this context in this paper.

The study of groundwater-sapping processes and their extension to stream piracy is complicated by the presence of surface water, which in many cases destroys evidence of groundwater sapping. For example, I have observed freezing groundwater in a vertical riverbank near Cook, Nebraska, that led to the dislodging of frozen bank material in meter-sized blocks during January 1999. Spring freeze-thaw cycles fragmented the blocks into transportable sediment that was carried away by a June flood. A July visitor would recognize significant bank erosion since the previous summer visit, but, because all evidence for groundwater sapping was destroyed, would attribute this to the June flood.

Figure 1. Erosion by needle ice growth in a road bank, Boone, North Carolina, USA. Groundwater extrusion represented by ice columns several cm long.

Lawler (1993) reported a similar result from needle-ice growth on the River Ilston, South Wales, United Kingdom. Prosser et al. (2000) found that needle-ice growth in winter and desiccation of clays in the summer control erosion on Ripple Creek Canal, Tasmania. Surface-water flows were unable to erode firm, cohesive clay banks that had not been preconditioned by groundwater sapping. I have found that needle-ice growth is responsible for road-bank erosion (Fig. 1) and erosion of lakeshore banks (Fig. 2).

Groundwater Sapping Examined

The effect of positive pore-water pressure in promoting erosion and increasing instabilities of slopes is well known. An expansion of the concept is needed to relate it to stream piracy. In computer modeling and laboratory studies (Howard, 1988b), headcuts spontaneously formed in response to groundwater seepage, and they migrated up gradient because of their intersection with the groundwater table where positive pore pressures occur, promoting erosion. With continued

Figure 2. Erosion by groundwater sapping (one week of freeze-thaw cycles) on shoreline bank of Lake Ashtabula, North Dakota, USA. With melting of lake ice, wave action removed the talus.

headward development, groundwater flow was focused in the few uppermost headcuts that interfered minimally with each other. These continued to erode headward, intercepting the groundwater flow that would have gone to the now-inactive headcuts. As groundwater-discharge energy in the form of positive pore pressures is rapidly focused in the few remaining headcuts, a consequent acceleration of headward erosion takes place, and a roughly parallel drainage network is developed. Dunne (1998) described a similar positive feedback in hollow formation. On a smaller groundwater-flow scale, Collison's (1996) simulations showed that even small soil cracks (enhancing recharge) just upstream from gully heads resulted in positive pore pressures at the base of the headcut. Collison (1996) also found that most eroded material transported by surface water originates in the gully itself rather than upslope, so the controlling factor for gully expansion should be headcut and wall instability. Flume experiments (Kochel et al., 1988; Baker et al., 1990) that modeled headcut migration under hydrogeologic conditions found in the Colorado Plateau yielded long valleys, short tributaries, and amphitheater heads, comparing well with the field description of Laity and Malin (1985).

The ability of a river to erode, transport, and deposit sediment is in part determined by interaction with the groundwater system. As an example, positive pore-water pressures in areas where groundwater discharges into a stream can increase the erodibility of the stream bed. Changes of erodibility and transport competency with groundwater influx and outflux in beach and stream settings can favor sediment accumulation or enhance erosion (Harrison and Clayton, 1970; Howard, 1988b; Butt and Russell, 2000).

Several case examples show the nature of the interaction of the groundwater-flow system and headcut migration in field settings of possible incipient stream piracy. Higgins (1984) observed that when the water table slopes at an angle less than that of the beach face, gully heads incise deeper as they advance updip. There is a threshold in gully depth where small slumps and block slides, due to deep entrenchment, negate further advancement. Where the water table parallels the beach face, gullies advance updip without increasing incision. By extension, to divide areas, if the water-table slope is less than the surface slope, increasing entrenchment would be favored where groundwater sapping is the dominant erosion process at the headcut. The development of a drainage network in the Finisterre Mountains in New Guinea (Hovius et al., 1998) may be similar to Higgins' beach example. Initial gorge incision is expanded by large-scale landsliding controlled by groundwater seeping, with the resulting debris being incised by fluvial erosion. Montgomery and Dietrich (1988) reported that channel initiation on steep slopes in the Coos Bay region of Oregon and in the southern Sierra Nevada is associated with landsliding that is probably caused by seepage erosion. In most settings, the actual sapping rates should be a function of groundwater-flow rates. Gabbard et al. (1998) found in laboratory studies that introduction of groundwater inflow caused accelerated headward erosion with erosion rates increasing by 60 times. The importance of groundwater-sapping erosion in geologic processes should not be overlooked (Higgins, 1984; Dunne, 1980; Schumm, 1980; Roloff et al., 1981; Netto et al., 1988). Dunne (1990) rated water as second only to gravity in producing slope instabilities.

> In broader terms, because of the great variety of groundwater-sapping processes and the nearly universal presence of groundwater, it is likely that most hillslope erosion and channel extension patterns carry the imprint (pattern) of groundwater-flow systems.

The Imprint of Groundwater Flow

In broader terms, because of the great variety of groundwater-sapping processes and the nearly universal presence of groundwater, it is likely that most hillslope erosion and channel extension patterns carry the imprint (pattern) of groundwater-flow systems. Freeze (1987) modeled the resulting water table between parallel rivers with given conditions of recharge and aquifer characteristics and coupled the output to slope-stability calculations to show effects of recharge from various precipitation events. His results showed that hydrogeologic factors coupled with climatic variation and short-term precipitation events exerted considerable control on the slope of the surface topography between the rivers in terms of stability of slopes and channel banks as controlled by pore pressures. His results suggest that the surface topography can be a reflection of the groundwater table as opposed to the popular concept of the water table being a subdued reflection of the surface topography. This suggestion is supported by the consequences of hillslope processes and the nature of channel extension in divide areas.

More specifically, groundwater sapping can be recognized by distinctive patterns of erosion occurring as a consequence of the geologic setting and regional and local groundwater-flow systems. Fyodorova and Sasowsky (1999) described the dissolution of quartz cement by groundwater leading to increased porosity and reduction of the mechanical strength of a sandstone. This weakening has led to additional groundwater-sapping processes becoming active with development of caves along preexisting fractures and joints within the sandstone bedrock. They suggest that dissolution of silica is transport controlled so the process is most active where fractures have been enlarged and groundwater has not adjusted chemically. (The bigger fractures with greater flow continue to grow.) Norris and Back (1990) described a similar evolution where mixing of groundwater and seawater leads to dissolution of carbonate rock along the Yucatan. It should be noted that groundwater is nearly as effective and rapid in erosion of siliceous rocks as of limestone rocks in terms of chemical weathering and removal of dissolved substances (Young and Saunders, 1986). Johnsson (1999) identified two sets (based on orientation and elevation) of horizontal cave passages associated with different historical elevations of the water table and directions of groundwater flow in the karst of Swago Creek in West Virginia. In each case, the fracture pattern of the rock and the direction of the groundwater gradient were contributing factors to the pattern of groundwater sapping. Nash (1996) found that the headward development of valleys in the Hackness Hills in North Yorkshire, England, was in part controlled by groundwater-sapping processes operating in an updip direction.

If groundwater-sapping location is a function of groundwater-flow systems and headcut interception, then groundwater-flow models should suggest patterns of development of stream drainages. In fact, drainage patterns based on groundwater-flow models using field hydrogeologic parameters and recharge rates show close agreement with actual field settings. Streams of a given order (in the sandy Pleistocene area of the Netherlands) can be explained as outcrops of groundwater-flow systems of a corresponding order reflecting the drainage density necessary to effectively drain the aquifer system (DeVries, 1976, 1994). DeVries (1995) expanded his work to include a model of contracting and expanding stream networks with groundwater-level change, as related to seasonal rainfall characteristics. Troch et al. (1995) applied DeVries's (1976) model to the Zwalmbeek catchment in Belgium. Coupled with the observation that in many humid lowland areas, overland flow is rare and so most flow is underground, they submitted that the existing drainage network developed through sapping erosion at the zone of groundwater exfiltration. In a setting comparable to that described by DeVries, the drainage network in the Sand Hills of Nebraska consists of roughly parallel rivers with no tributaries. The drainage-network density corresponds to the thickness of the underlying aquifer; it is less dense where the aquifer is thicker and was likely developed by headward erosion caused by groundwater sapping (Pederson, 1995).

The Groundwater-Sapping Model of Stream Piracy

The principal fact favoring stream piracy by groundwater sapping is that the groundwater divide does not correspond to the surface-water divide when there is a difference in elevation of streams in the adjacent drainages (Fig. 3). Because of this, the groundwater-flow system does not lose its energy with gully extension like the surface-water system does with its decreasing catchment size. Three selected stages of channel extension across a divide are shown in Figure 3.

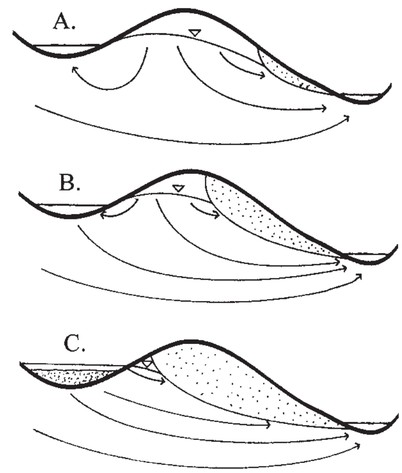

Figure 3. Cross-section sequence (A–C) of pirating channel extension and eventual divide breaching by groundwater sapping. Arrows show paths of groundwater flow and inverted triangle shows position of water table. Sedimentation in pirated stream shown by higher density of dots. Erosion in pirating channel shown by lower density of dots.

In stage A, a tributary of the pirating stream is extending itself by headward erosion toward the divide. Groundwater flow is focused, much like flow to a pumping well. The energy driving the groundwater-flow system is reflected by the difference between the elevation of the groundwater divide and the elevation of the water-table outcrop at the headcut. The energy of the surface-water system would be the difference between the topographic divide and the base of the headcut. Note, no mass considerations or energy conversions that occur along the flow paths are included, so this is not a measurement of the actual energy available at the headcut for erosion. The elevation and location of the groundwater divide represents a dynamic equilibrium that will change with climatic changes and changing geometries such as channel extension.

Continued headward erosion of the extending channel results in a migration of the groundwater divide toward the soon-to-be-pirated stream. More of the regional recharge to the groundwater-flow system is now moving toward the extending channel in stage B (Fig. 3) with a likely increase in groundwater-sapping potential. At some point in time, the soon-to-be-pirated stream will start losing flow to the groundwater system, which will further increase the groundwater-sapping potential. At this point, the potential exists for the initiation of sediment accumulation in the pirated channel. In contrast, the energy for headcut erosion by surface water is decreasing because of the decreasing catchment size.

In stage C (Fig. 3), the pirated stream is losing considerable flow to the groundwater system and the potential for sediment accumulation is high. Breaching of the topographic divide was possible because the groundwater-flow system is able to maintain its energy and, in fact, may experience an increase in energy gradient as the pirated stream is approached by the extending channel of the pirating stream. An additional increase in energy in the groundwater-flow system will occur with the accumulation of sediment in the pirated stream. A positive-feedback situation develops in which losses of water from the pirated stream augment the groundwater-sapping process, leading to further sediment accumulation and other outcomes.

While the basic process shown in the model is the same in heterogeneous and anisotropic settings, the actual flow paths followed by groundwater in these settings may modify the geometric pattern shown in Figure 3. Also, developing fracture flow or development of karst (limestone or rock with soluble cement) may cause stream piracy to occur well before there is an apparent surface expression. It is only a matter of time before the subsurface flow paths would be expressed at the surface.

It is very difficult to identify areas of incipient stream piracy on a large scale because the process is slow compared to the human time scale, and the quantification of channel extension rates is complicated by the nonlinearity of the erosion system. It is also very difficult to determine past rates of stream piracy because the evidence has usually been destroyed. Having said that, the proposed model of stream piracy by groundwater sapping should work on all time and size scales as the mechanics should operate at all scales.

SURFACE WATER AND STREAM PIRACY

The basics of a "surface water view" of stream capture (the other potential villain) were described by Crosby (1937) and are still found in many textbooks. Erosion is "gnawing back at the headwaters of every stream" (p. 469) with the rate of erosion dependent on the formations present, slope of the land, climatic conditions, and protecting vegetation. Weathering breaks rocks into fragments, which are transported by hillslope processes—including sheetwash, landslides, and soil creep—to stream channels where they are transported. Rates of erosion are controlled by water velocity, abrasion tools, and the underlying formation. Crosby acknowledged the "apparently impotent little brook" (p. 471) in the headwaters, but credits weathering between floods for wearing away these rocks and the floods themselves for removing sediment.

There are many complicating factors in determining the mechanisms and rates for channel extension. Weissel and Seidl (1997) found that while bedrock lithology and upstream drainage area had minimal impact on knickpoint retreat, bedrock jointing profoundly affected the hillslope processes that control knickpoint migration rates. Whipple et al. (2000) determined that the efficacy of fluvial erosion processes (plucking, abrasion, cavitation, and solution) was a strong function of substrate lithology and that joint spacing, fractures, and bedding planes exert the most direct control. Montgomery and Dietrich (1989) identified thresholds of upslope catchment area needed to erode a channel head. As a channel head approaches a divide, the catchment area will decrease, reducing runoff. Gomez and Mullen (1992) recorded more than 90% of network growth in the first 10% of their experiment's duration. An exponential curve for gully extension was suggested by Rutherford et al. (1997). A broader interpretation is that intrinsic and/or extrinsic factors may provide a threshold for initiation, and the physical effect of channel extension "exhausts" these factors.

Figure 4. Rainbow Falls, near Hilo, Hawaii, USA. There is a clear undercutting of the falls' face well beyond the zone of plunge. The presence of adjacent springs and water flowing from the cavelike feature suggests a complex system of knickpoint advancement in this setting.

STREAM PIRACY: GROUNDWATER AND SURFACE WATER AS COOPERATORS

Water, the common element of surface water and groundwater, is obviously the major initiator and accelerator in erosion and the key element in stream piracy. The hardest rock can be broken down by freeze-thaw cycles, and a cohesive sediment can be fragmented by wet-dry cycles. Fractures in an "impermeable" rock leave them vulnerable to erosion and enlargement by water. Water supports living organisms that condition rock and sediment for erosion, and it can dissolve interstitial cement and the rock itself. Where there is water movement, there is an increasing probability of a chemical disequilibrium between the rock and the interstitial water. Positive pore-water pressure undermines slopes, triggers landslides, and contributes to debris flows. As water erodes, it usually creates a preferred flow path, further accelerating the erosion process. Groundwater-sapping processes are equally effective in the presence of surface water, but they are often not recognized because either the evidence is destroyed by surface water or they are lumped under hillslope processes. Because of the inertia of the system, groundwater sapping is more continuous and persistent over time as compared to surface water.

Groundwater energy is little affected by topographic divides as compared to surface-water energies. Surface-water energy usually decreases near divides because of shrinking catchment areas and sometimes decreased surface gradients. With breaching of the divide, considerable erosion would be required to develop a catchment area for surface runoff to feed the pirating stream on the pirated stream side of the drainage basin. This is unlikely because nearly all sediment comes from the extending channels. If there is insufficient flow in the channel, accumulating sediment in the headcut can slow the erosion process, so availability of sediment transport may control the rate of extension. This fact is an argument for the occurrence of stream piracy being most likely during wetter climatic periods. Finally, extension of a channel is often very rapid at first, implying that a threshold has been crossed. This also suggests that the final act of stream piracy should occur as the consequence of an event rather than as the continuation of an average.

The only connection between the

pirated and incipient pirating stream is through the groundwater-flow system (Fig. 3). The incipient pirating stream can gain flow (sapping energy) from the pirated stream. The pirating stream can cause the accumulation of sediment in the incipient pirated stream. This concept should apply in the building and breaching of river levees, delta formation, alluvial fans, and hillslope processes.

Most stream piracy is likely the result of a succession of channel extensions in response to climatic events. One must recognize that the current climatic conditions may not be the same as when stream piracy occurred. Just as short-term precipitation events accelerate groundwater-sapping erosion and surface-water erosion, longer climatic events can add or remove energy from the pirating equation, including base-level changes. Higgins (1984) proposed that the pectinate (comb-like) drainage networks of the High Plains were formed chiefly by groundwater sapping when the water tables were higher during wetter climates of the past. Alley (2000) highlighted the relative stability of the climate over the past 10000 yr as compared to the much larger instabilities of the past 100000 yr, so our historical perceptions may be inappropriate in interpreting stream piracy. The rates of surface processes and denudation (Young and Saunders, 1986) are such that many stream-piracy events likely occur over time scales greater than the current period of climate stability, especially in lithified and cohesive material. However, of all natural variables controlling surface water and groundwater flow in general, only climate can change significantly over time periods shorter than geologic time. An exception to the previous statement may occur with disruptions of drainages during earthquakes, volcanic activity, and subglacial drainage events. On an even shorter time scale, several years of unusually high precipitation can significantly increase the erosive power of groundwater and surface water.

SUMMARY

Groundwater exists in nearly all geologic environments in a dynamic system with persistent flow from recharge areas to discharge areas where groundwater-sapping processes are focused. Groundwater sapping is highly effective in eroding sediment and rock. The presence of perennial surface water is strong evidence for groundwater intersecting the surface and for effective groundwater sapping. Groundwater sapping is effective in the absence of surface water. Unfortunately, the evidence for groundwater sapping is usually destroyed by surface water.

Headward extension of channels results in a distortion of the groundwater-flow system. The head of the channel represents a low potential energy point for groundwater flow, much like a pumping well. With concentration of flow, groundwater-sapping processes are concentrated at the headcut, resulting in further channel extension and/or incision that in turn leads to increasing incision of the groundwater-flow system. There is the potential for the development of thresholds that, on being exceeded, can lead to rapid channel extension. An analogous event would be the failure of the Teton Dam.

Groundwater sapping should be suspected at locations where the surface morphology suggests incision into the groundwater table and concentration of groundwater flow. A greater potential for groundwater sapping is found at the outside of meander bends, at the point where streams become live, where riverbanks feel spongy, where talus slopes form during freeze-thaw cycles, and in deeply entrenched channels. Groundwater sapping may be found in areas where banks and slopes are wet or undercut or have zones of vegetation growth, surface evaporitic deposits, desiccation cracks, water flow from fractures, and evidence of soil flow. If the setting appears too dry, try visualizing a long-duration thunderstorm and a much higher groundwater table.

If there is a difference in elevation of streams in adjacent drainage basins, the topographic divide does not correspond to the groundwater divide (Fig. 3). As a result, the groundwater-flow system maintains its energy as the headcut approaches and crosses the topographic divide, because its energy comes from the groundwater divide. In contrast, the energy of surface water at the headcut decreases as the divide is approached because of reduced catchment area and possibly reduced surface gradients.

Only the groundwater-flow system has the potential for pre-piracy "communication" between the pirating and pirated stream (Fig. 3). The pirated stream can provide flow and potential energy to the groundwater system. This can further enhance groundwater sapping at the headcut of the extending pirating stream. As the pirating stream advances, the changing groundwater-flow paths (Fig. 3) can cause a loss of flow in the pirated stream, resulting in sediment accumulation in the bed as stream competency decreases. This can in turn lead to an increasing energy gradient in the groundwater-flow system.

A heterogeneous and anisotropic geologic environment would modify the actual groundwater-flow paths, but the overall results would be similar to the homogeneous and isotropic model shown (Fig. 3). Karst development would occur along fractures and higher permeability zones, reflecting the imprint of the groundwater-flow system from recharge to discharge areas. Fractures zones would enlarge and grow in a similar manner.

Because groundwater sapping is a basic geologic process, and energy gradients can exist at all scales, the stream-piracy model presented in this paper should be applicable at all time and size scales. Stream piracy is a possibility on the smallest streams and the largest intermountain drainage basins. Where diversion has occurred, groundwater sapping should be suspected.

This model suggests that higher energy gradients would be expected during wetter climatic periods, and as a consequence, channel extension should be more rapid during these periods. The increased rate of channel extension under wetter climatic conditions is intuitive in part, but by extension, it also means that the actual stream diversion is most likely during wetter climatic periods.

Lane (1899) promoted the role of groundwater sapping in stream piracy. Unfortunately, the visibility of surface water and the lack of understanding of groundwater-flow and groundwater-sapping processes have led to a long advocacy of surface water as the pirating villain. Waterfalls (e.g., Fig. 4; cover photo) on the Island of Hawaii demonstrate that factors other than surface water alone must be at work in knickpoint migration. There is considerable evidence for groundwater sapping in these two localities using criteria discussed in this paper.

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