Fracture intersections as integrators for unsaturated flow

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[1] A simple experiment finds that fracture intersections can act to integrate unsaturated flows, such that regular, low flows entering the intersection from above are transformed into large, less frequent pulses below. At low flows, our simple intersection forms two capillary barriers. Water from above pools at the intersection until sufficient pressure builds to breach the barriers and discharge stored fluid. The barriers then reform and the process is repeated. At low flows, the volume discharged from the intersection remains relatively uniform across a range of flow rates. At higher flows, discharge volume is highly variable, and a viscous stabilized non-pulsating regime occurs at the highest flow rate that we considered. *INDEX TERMS:* 1875 Hydrology: Unsaturated zone; 1829 Hydrology: Groundwater hydrology.

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1. Introduction

[2] Recent laboratory experiments have shown that steady application of fluid to the top of an unsaturated fracture-matrix network can produce dynamic preferential pathways, with flow fluctuating both along individual paths, and between alternate pathways [*Glass et al.*, 2002]. Magnitude of the observed fluctuations was larger than could be explained by pulsation or dripping along gravity-driven fingers within individual fractures [e.g., *Nicholl et al.*, 1993; *Su et al.*, 1999]; the possibility of fracture intersections acting as gates was suggested as an alternate hypothesis. In this conceptual model, fracture intersections form capillary barriers that accumulate flow from above, release the integrated volume when the barrier is breached, and then reestablish the barrier to begin a new cycle.

[3] Here we present an experiment that considers downwards unsaturated flow across a simplistic intersection. At the highest flow rate considered, we observed a viscous stabilized regime in which flow was not influenced by the intersection. At low pulsed flow in the upper fracture was integrated by the intersection, and released into the lower fracture as less frequent pulses of larger volume. Between these two regimes, we observed a transition zone characterized by highly variable behavior.

2. Experimental Design

[4] Recognizing that the geometry of fracture intersections may vary widely in nature, we focus here on a simplistic intersection in which a vertical fracture is bisected by a horizontal fracture (Figure 1). Four limestone blocks (porosity ~15%) were cut to nominal dimensions of 5 × 7 × 30 cm, lightly sanded to smooth the surfaces and square the corners, and then soaked in chemically equilibrated water to satisfy imbibition. The four blocks were clamped in a simple enclosure (Figure 1) that restricted evaporation, left all fracture edges open to atmospheric pressure, and allowed an unobstructed view into the fracture planes and intersection. Fracture apertures were held open to ~0.06 cm with small (~5 mm long) shims, yielding a saturated hydraulic conductivity (~2×10^3 cm/min) much larger than the measured value for the limestone blocks (~7×10^{-5} cm/min). Equilibrated water was supplied to needles inserted into a 5 cm long fiberglass wick pressed along the top of the vertical fracture, and effluent was allowed to drain freely through the bottom of the system.

[5] To focus specifically on behavior at the intersection we employed optical sensors to monitor the occurrence (and absence) of flow in the vertical fracture. Each sensor was formed by positioning a light emitting diode (LED) and a photoelectric cell on opposite sides of the 5 cm wide fracture (Figure 1). With the fracture empty, the light path between a photocell and corresponding LED was unimpeded. Water spanning the fracture aperture (i.e., in contact with both fracture walls) introduces refractive air-water interfaces that interfere with light transmission, and thus decrease output from the photocell (see Figure 2). Two optical sensors were located in the upper vertical fracture (24 cm and 7 cm above the intersection), and two in the lower vertical fracture (4 cm and 23 cm below the intersection). The intersection itself was left unobstructed to facilitate visual observation.

[6] In preliminary tests, we found that a transition between intermittent and stable flow regimes occurred at a supply rate of ~8 ml/min. We also observed that flows down to ~0.2 ml/min were large with respect to evaporative losses. Based on these observations, we started our experiment with a flow rate of ~8 ml/min and then decreased flow over a series of 1+ hour steps, stopping at

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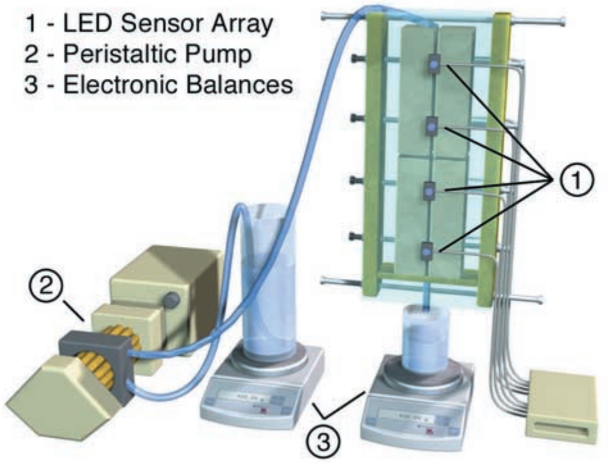

Figure 1. Sketch of the experimental system. Faces of the frame were covered in rigid plastic sheeting to retard evaporation.

0.23 ml/min. This range of flow (~8 to 0.23 ml/min) corresponds to ~1.3 to 0.038%, respectively, of the flow we would expect in this fracture under fully saturated, unit gradient conditions (~600 ml/min). Throughout the test, we collected data from the optical sensors at 20 millisecond intervals. To assure consistency of boundary conditions, we also took gravimetric measurements of inflow and outflow at 2 second intervals. Finally, at each flow rate we recorded visual observations of behavior within the fractures and the intersection.

3. Results

[7] At our initial flow rate (~8 ml/min), both horizontal fractures were filled to their edges, and the upper fracture was filled to a depth of ~2 cm above the intersection, forming a 'pool'. Flow from the source to the pool occurred as a thin continuous 'tendril' in contact with both walls of the vertical fracture; a similar tendril connected the pool to the bottom of the system. Assuming a unit gradient and flow between parallel plates, we calculated the tendrils to be ~0.06 cm wide.

[8] As we stepped down the flow rate, tendrils above and below the intersection became unstable, breaking and reforming. After a tendril broke, a fluid pulse would move down from above as a relatively large 'blob' with a long, thin tail; similar features were observed by *Su et al.* [1999] in a parallel plate fracture with glass walls. Where sufficient flow was available, the tail could develop into a new tendril spanning the fracture. At yet lower flows, fluid moved through the fractures as discrete pulses, with the intersection acting to integrate flow by accumulating small pulses from above, and releasing fluid into the lower fracture as less frequent pulses of larger volume.

3.1. Optical Data

[9] Figure 2 shows signals measured by our four sensors over arbitrarily selected 15 second intervals at three different flow rates. Data for the individual sensors have been shifted vertically to appear in the same order as in the experiment, from top to bottom. At low flow (e.g., 0.4 ml/min), fluid moved through the upper fracture as regularly occurring discrete pulses ~1 cm in length; seen in Figure 2 as downward spikes (black, red). At increased flow, pulses in the upper fracture become closer together (0.8 ml/min), and then change from spikes to more complicated features (1.5 ml/min). At 1.5 ml/min, pulses crossing the topmost sensor (black) show a downwards spike followed by a partial return towards baseline, then a rapid return to baseline. This signal corresponds to a pulse that develops a short-lived tail. Because most light loss occurs at the air-water interfaces and not within the fluid, the tail can be much thinner relative to the leading edge (or head) of the pulse and still block nearly as much light. The lack of a tail in data collected by the 2nd sensor (red) at 1.5 ml/min suggests that the fracture aperture may widen slightly with depth.

[10] In the lower fracture, pulses were less frequent and of considerably longer duration than was observed in the upper fracture, both features indicative of integration at the intersection. We also noted larger voltage deflections and more complex signals in the lower fracture. Voltage signal from the 3rd sensor (blue) shows that duration of the tail at this location increases with flow rate. At yet higher flow rates (>2 ml/min), the tail reached sufficient length to form a tendril of fluid conducting flow along the fracture plane. The bottommost sensor (green) shows more erratic behavior, where a long duration pulse may be closely followed by one or more pulses of much shorter duration. The formation of such doublets (or triplets) appears to result when the tail of a pulse broke between the 3rd and 4th

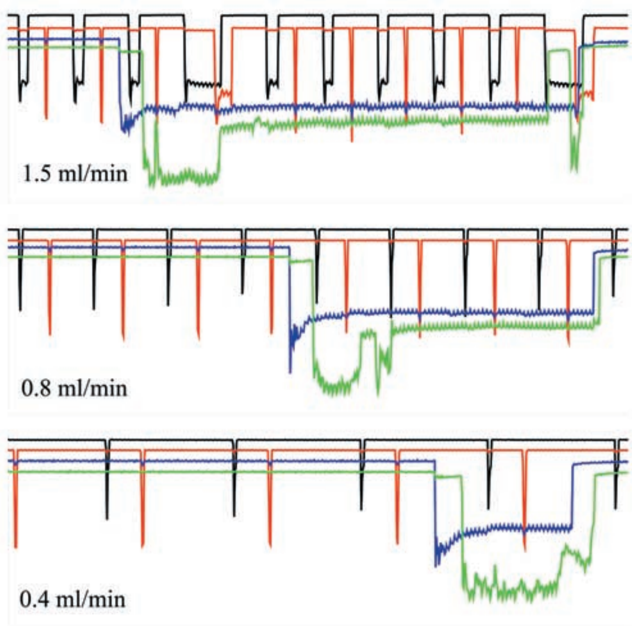

Figure 2. Optical sensor data. Individual voltage traces for sensors 1–4 have been shifted vertically for presentation: 1 (top, black), 2 (red), 3 (blue) 4 (bottom, green). The degree of deflection from baseline voltage remains unchanged from the original range of ~0.2 to 0.5 volts. Noise levels are highest when the light transmission is blocked by aperture spanning water, and ambient light contributes significantly to the signal.

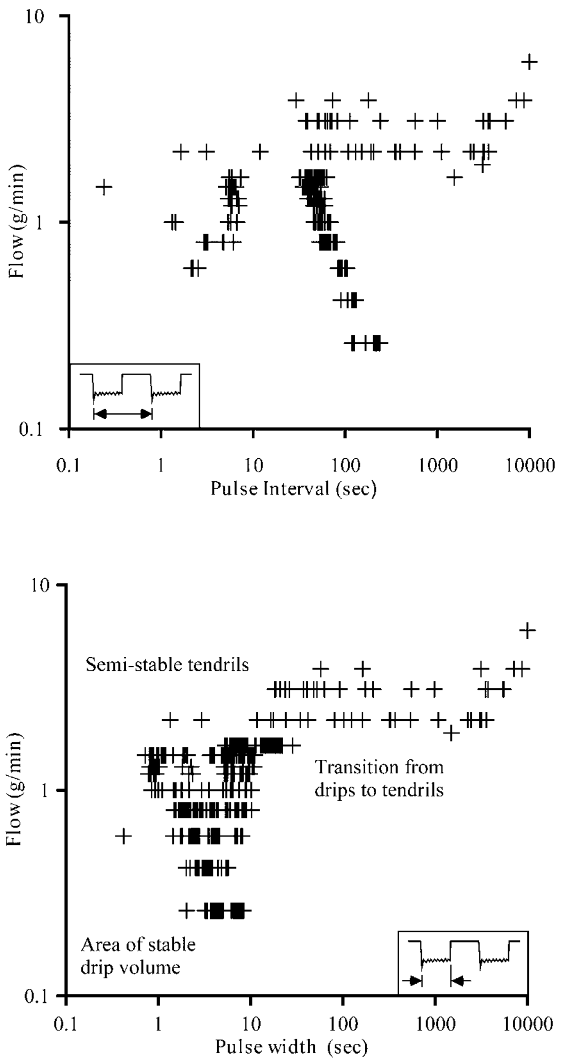

Figure 3. Pulse Interval (a) and Pulse Width (b) at optical sensor number 3. Insets illustrate how the data was evaluated to obtain these measures. Data are shown on log-log axes to accommodate the wide range of observed data; for clarity, supply flow is shown on the vertical axis. Much of the data at a given flow rate plots on top of one another.

sensors. Fragmentation of the tail may be associated with local aperture variability or pulse length.

3.2. Pulse Interval and Pulse Width

[11] We defined pulse interval as the elapsed time from the leading edge of one pulse to the leading edge of the following pulse (Figure 3a). We also defined pulse width as the elapsed time between the leading and trailing edges of an individual pulse (Figure 3b). Both pulse interval and pulse width were evaluated as a function of flow rate for sensor 3, located 4 cm below the intersection. At the highest flow considered (~8 ml/min), pulse interval (Figure 3a) and pulse width (Figure 3b) are identical (~10,000 s), as a tendril persisted for the duration of flow at this rate. As we stepped down the flow rate, the tendril below the intersection became unstable at a flow rate of ~6–7 ml/min. At ~2 ml/min, snapping and reforming of the tendril became increasingly frequent; during this time, pulse interval and pulse width varied over orders of magnitude.

[12] As the flow rate was dropped below ~2 ml/min, we observed a transition from tendrils to pulses, where a long pulse interval was often immediately followed by one or more short intervals. Below this transition, and down to the smallest flow rates considered, pulse widths remained relatively constant, with a mean of about ~3–4 s (Figure 3b). Pulse interval steadily increased over the same range of flow (Figure 3a), suggesting that discharge from the intersection involved a relatively constant storage volume. At the lowest flow considered (~0.23 ml/min), pulse interval was on the order of 200 s, while pulse widths were ~5 s, suggesting that the intersection integrated flow by a factor of ~40, with a storage volume of ~0.8 ml. At this low flow rate, there is little or no recharge to the stored volume during a discharge event, effectively isolating the two processes from one another and suggesting a well defined storage volume. At higher flow, replenishment of intersection storage during discharge couples the two processes, thus changing the balance between forces (viscous, gravity, capillary), and leading to a more complex discharge signal.

3.3. Intersection Invasion Process at Low Flow

[13] In the low flow regime, flow was integrated when our simple intersection acted as a capillary barrier, causing water to pool. Visual observation shows that accumulation and discharge of water at the intersection followed a six-step process (Figures 4a–4f), during which two capillary barriers are breached:

a. Following a discharge event, both horizontal fractures are partially filled, and a small pool of fluid is left above the intersection. Initially, the menisci of these three fluid bodies are not in contact with one another. The pool in the right-hand horizontal fracture contacts almost the full width of the intersection; on the opposite edge, the pool is curved in the plane of the fracture and terminates ~1 cm from the far right-hand edge of the fracture. The pool in the left-hand fracture extends fully to the far left-hand edge of the fracture, but is retracted by ~0.5 cm from the intersection, where it displays macroscopic interfacial curvature along the retracted surface.

b. The surface of the pool above the intersection rises with continued addition of water. Increased fluid pressure causes the meniscus along the bottom of the pool to flatten downward until it connects with fluid in the right-hand fracture, breaching the first capillary barrier.

c. The upper surface of the pool drops slightly as water flows into the right-hand fracture; addition of water causes the horizontal pool to grow away from the intersection toward the far right hand edge of the fracture.

d. When storage in the right-hand fracture is filled, the upper surface of the pool begins to rise again. Increased fluid pressure causes the meniscus connecting the upper and right-hand fractures to grow downward into the intersection.

e. When this lower meniscus touches the upper corner of the lower left-hand brick, the second capillary barrier is breached (image shown is just prior to contact). Note that the fluid pressure (pool height) required to breach this second capillary barrier is greater than for the first (step b).

f. Water rapidly fills the intersection, connecting with the existing pool to fill the left-hand horizontal fracture, and

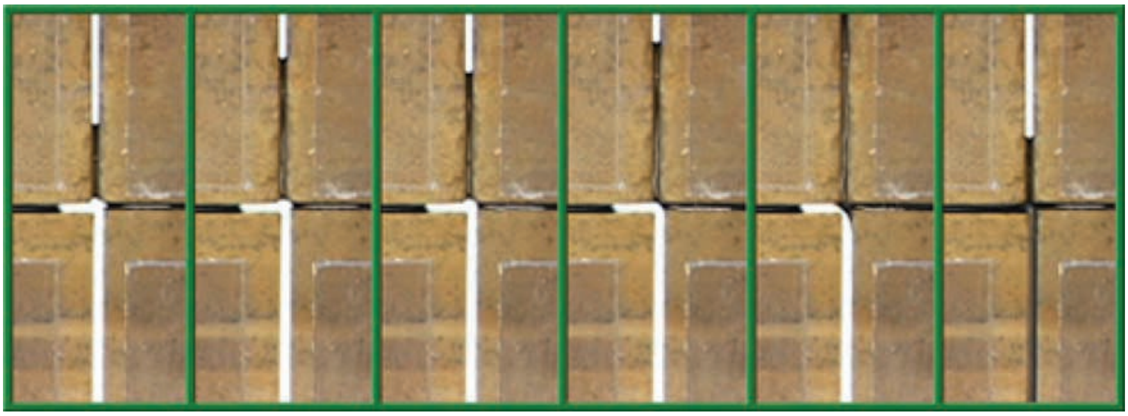

Figure 4. Intersection invasion process. Time lapsed images of fluid accumulation and discharge that occurred over an ∼40 second period at a flow rate of ∼1 ml/min. Each image shows an 3.5 cm high by 1.8 cm wide region about the intersection; dark areas within the fractures are occupied by water, while the light areas are empty. Darker rectangles on the bricks, away from the intersection, are part of the plastic window used to restrict evaporation, and do not affect the flow field.

invading the lower fracture as a gravity-driven finger. The pool above the intersection decreases to a minimum as water flows out of storage in both the upper and right-hand horizontal fractures. The finger thins to a tendril as stored water is depleted. The thinning tendril eventually "snaps", vacating the intersection to produce a condition similar, but not necessarily identical to that at the beginning of the process (step a). The sequence b–f is then repeated.

[14] Clearly, the degree of integration caused by the intersection will be strongly dependent on the oscillatory storage volume (maximum-minimum) formed by the capillary barrier(s). In our experiment, coupling between pools above the intersection and in the right-hand horizontal fracture allowed a larger degree of integration than would have occurred with either of the pools individually. Note that the pool in the left-hand horizontal fracture was only connected during discharge events, and hence did not contribute to integration between events.

4. Conclusions

[15] At low flow rates, we find that a simple idealized fracture intersection acts to integrate unsaturated flow, taking a high frequency, low volume inflow and transforming it into a low frequency, high volume outflow. Observations show that this integration is accomplished by the repeated accumulation and discharge of fluid as a sequence of two capillary barriers at the intersection are first established, and then subsequently breached. The integration volume appears to be well defined, with a small range of fluctuation. As flow rate increases and viscous forces become important, pulsating flow transitions to a stable configuration where the intersection no longer behaves as a gate.

[16] We emphasize that we considered only one possible intersection geometry from a myriad of possibilities expected in nature. Also, during our design phase, we observed that in addition to integration, fracture intersections can generate other interesting behavior, such as: multiple tendrils, snap off into the horizontal fracture, migrating tendrils, and spontaneous switching between tendril and dripping behavior at a constant flow rate. Furthermore, it is possible that the viscous stabilized regime we observed may become unstable for unsaturated flows of greater magnitude than those considered here. Given these possibilities, flow integration and other behavior at fracture intersections may pose a significant challenge for conceptualizing unsaturated flows within fracture networks.

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