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Injection System for Multi-Well Injection Using a Single Pump

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Abstract

Many hydrological and geochemical studies rely on data resulting from injection of tracers and chemicals into groundwater wells. The even distribution of liquids to multiple injection points can be challenging or expensive, especially when using multiple pumps. An injection system was designed using one chemical metering pump to evenly distribute the desired influent simultaneously to 15 individual injection points through an injection manifold. The system was constructed with only one metal part contacting the fluid due to the low pH of the injection solutions. The injection manifold system was used during a three-month pilot scale injection experiment at the Vineland Chemical Company Superfund site. During the two injection phases of the experiment (Phase I = 0.27 L/min total flow, Phase II = 0.56 L/min total flow), flow measurements were made 20 times over three months; an even distribution of flow to each injection well was maintained (RSD <4%). This durable system is expandable to at least 16 injection points and should be adaptable to other injection experiments that require distribution of air-stable liquids to multiple injection points with a single pump.

Introduction

Many field-scale experiments involve introduction of tracers and other liquids to the subsurface via injection wells for the purpose of defining hydrological parameters or aquifer heterogeneities at a field site, enhancing microbial activity, transforming contaminants into less toxic forms, etc. (Gouze et al. 2008; Istok et al. 2004; Mailloux et al. 2003a; Schroth et al. 1998). In particular, recent experiments have involved injection of tracers, biotracers, nutrients, microorganisms, etc. to the subsurface at multiple injection points (Harvey and Garabedian 1991; Kennedy et al. 2006; Mailloux et al. 2007; Mailloux et al. 2003b; Sandrin

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Photographs of various views of the injection system in use at the Vineland site.

Table S1. List of parts used to create the injection system.

Table S2. Details of flow monitoring during the Vineland injection. Tabular presentation of Figure 2.

et al. 2004). When multiple injection wells are used, it can be difficult to introduce chemicals and tracers consistently and evenly over time. The use of multiple pumps or pump heads is a common method for influent introduction to multiple wells (Harvey and Garabedian 1991; Mailloux et al. 2007; Mailloux et al. 2003b; Sandrin et al. 2004) but this can become logistically complicated or cost prohibitive. As an alternative to using multiple pumps one can perform sequential experiments (Istok et al. 2004), yet, this is not always feasible due to time constraints or desired experimental design. Therefore, injection manifold systems for distribution of liquids to multiple injection wells are a potential solution; however, the design of injection systems is rarely published in detail (Gouze et al. 2008; Mailloux et al. 2003b; Schroth et al. 1998).

Here we describe an injection manifold system that can simultaneously and evenly distribute liquids to many injection points with a single pump. The motivation for design of this injection system was the need to introduce a solution of reagents and tracers to 15 individual wells at a total injection rate of 0.27 (Phase I) to 0.56 L/min (Phase II) during a three-month pilot experiment using a single chemical metering pump. While the data presented here describe use of the injection system at one specific site, this type of system could be adapted to many other field locations and to other experimental designs using multi-well configurations and where even flow distribution is desired.

Design Considerations

Division of flow from a single source to multiple outlets is a common engineering problem used in applications such as irrigation systems, gas burners, water supply systems, and sewage disposal (McNown 1954; Rawn et al. 1961; Roberson et al. 1998). To design a system that maintains even distribution of flow, it is important to consider the various factors that impact flow through pipes or tubes and work to minimize differences in discharge at each outlet point. For a system with laminar pipe flow (like the one in our design), Hagen-Poiseuille's law states that the flow rate is proportional to $r^4 l^{-1} \mu^{-1} \Delta h$, with r and l being the radius and length of the pipe, respectively, Δh the difference in hydraulic head, and μ the viscosity (Hornberger et al. 1998). Consequently, flow out of individual ports is very sensitive to the radius of the tubes and somewhat sensitive to temperature-controlled changes in viscosity, the length of individual tubes and the hydraulic head distribution in a manifold system, which is a function of elevation, for example.

By keeping the system small, variations in r , l , Δh , and μ (which is a function of temperature) can be minimized. Also, leveling of the manifold and its input and outputs will equalize the hydraulic head differences between the individual ports. By keeping the inner diameter of the manifold large compared to that of the individual discharge tubes, the head loss due to friction along the manifold is negligible compared with that in the small diameter discharge tubing, resulting in a relatively uniform hydraulic gradient along the small diameter tubes.

Finally, surface effects may also play a role in creating flow rate differences at the multiple outlet points. By pulsing the pressure in the manifold, water is ejected rapidly out of the individual ports (versus constant dripping), reducing the effects of surface tension.

Additionally, the high flow velocity in individual pulses minimizes opportunity for precipitation of dissolved salts, which could change the diameter of the outlet point and thus impact flow rates.

Materials and Methods

Overview

This injection manifold system was used as part of a pilot scale injection experiment at the Vineland Chemical Company Superfund site. The site is located in southern New Jersey and is underlain by the sandy sediments of the Kirkwood-Cohansey aquifer system. Due to years of improper chemical storage and disposal by the Vineland Chemical Co., the site's groundwater and subsurface soils are extensively contaminated with As. Despite nearly 10 years of pump and treat remediation, groundwater As concentrations at the recovery wells can be several hundred $\mu\text{g/L}$ while the US drinking water standard is 10 $\mu\text{g/L}$. Additionally, the aquifer sediments have become contaminated with typical As concentrations of 20–250 mg/kg; these sediments act as a source of As to the groundwater. Laboratory work has been conducted which shows that introducing oxalic acid to As contaminated sediments can increase As release and may potentially accelerate As remediation at sites using pump and treat technologies (Wovkulich et al. 2010). The injection system was used during a pilot scale injection experiment where the ability of oxalic acid to release As was tested in a field setting (Wovkulich et al. in preparation).

The injection system needed to run continuously for three months to inject chemicals and tracers. In the pilot area, five injection well nests, with three 1" wells per nest, were installed for a total of 15 wells. In each well nest, the wells were screened at 27–28 ft (8.2–8.5 m), 29–30 ft (8.8–9.1 m), and 31–32 ft (9.4–9.8 m) below ground surface (bgs); the water table is approximately 15 ft (4.6 m) bgs. The injection manifold was mounted on top of one of the well casings and was used to inject chemical solutions and tracers (pH ~1, density up to 1.013 kg/L) to 15 wells over the course of the three-month experiment. The total flow rate was 0.27 L/min (18 mL/min per well) for the first 34 days (Phase I) and 0.56 L/min (37 mL/min per well) for the next 56 days (Phase II). During the three-month experiment, flow rates were measured 20 times at a subset of the wells to ensure the even distribution of solutions; the flow at each outflow point was collected into a graduated cylinder for two minutes and the volumes recorded. Additionally, at the end of the injection experiment, the pump settings (speed and stroke) were varied and the flow rates were monitored to evaluate the distribution of flow at each outflow point.

Description of Injection System

A model C131-26S, LMI Milton Roy chemical metering pump (Ivyland, PA) was chosen for the experiment because of its ability for continuous pumping over long time periods (months), chemical resistant design, and desirable output flow range; pump function is based on movement of a diaphragm which is driven by an electromagnetic solenoid. The goals for the design of the injection system were (1) use a single pump, (2) evenly distribute flow from that pump to 15 outflow ports, and (3) use inexpensive and readily available materials. Because of the low pH of the solutions being injected in this experiment, the injection

system was designed such that no metal parts would come in contact with the fluids (except for one small, replaceable metal spring in the pump). The system can only be used with fluids that can come in contact with the atmosphere. Photographs of the injection system set up can be found in the online Supporting Information (Figure S1).

The chemical metering pump was mounted above a 300-gallon (1136 L) polyethylene tank with the pump's polyethylene tubing and foot valve extending into the tracer reservoir through a hole cut in the cap of the tank. In this design, liquid flows from the chemical metering pump through approximately 40 ft (12.2 m) of 3/8" PVC tubing (Figure 1A-7) to a tube fitting tee (Figure 1A-8) where the liquid is split evenly to either side of the injection manifolds (Figure 1A-5); liquid reaches the manifolds after passing through tube-to-pipe elbows (Figure 1A-6). Hose clamps were used to secure tubing to the tube fitting tee and the tube-to-pipe elbows that led to the manifolds. The liquid is then pushed from the manifolds through pipe-to-tubing adapters (Figure 1A-2) to narrow diameter tubes (1/16") that are 8.7" (22.2 cm) in length (Figure 1A-1). As mentioned in Design Considerations, the inner diameter of the individual discharge tubes were small compared with that of the manifold; this kept the frictional head loss along the manifold negligible compared with that in the 1/16" tubing and allowed for a relatively uniform hydraulic gradient along the 1/16" tubes once maximum tubing height and tubing length were made consistent.

The manifolds come with 4 or 8 outlets; outlets can be fitted with a hex hollow plug (no flow) (Figure 1A-3) or pipe-to-tubing adapters (flow) (Figure 1A-2) to achieve the desired number of outflow points. Additionally, two manifolds can be joined (Figure S1B and Figure 1A) with a pipe hex nipple (Figure 1A-4) for applications requiring more than 8 outflow ports. The manifolds are mounted to a horizontal PVC plate (Figure S1C). The 1/16" tubes are threaded through holes in a vertical PVC plate (Figure 1B-16) such that the height of each tube is identical; differences in tube height could lead to uneven distribution of flow. The 1/16" tubing is then threaded through holes cut in plastic plugs (Figure S1C; Figure 1B-17); vent holes are also cut in these plastic plugs. The plastic plugs are fitted into thru-wall adapters (Figure 1B-21), which have been tapped into the horizontal PVC plate (the manifolds are also mounted to this plate). The pieces of 1/16" tubing end at the bottom of the thru-wall adapters; each piece of tubing ends at the same height to ensure even distribution of flow. The 1/16" tubes were kept in the center of the thru-wall adapters by winding electrical tape around the 1/16" tubes; siphoning effects could result if the 1/16" tubing is in contact with the sides of the thru-wall adapters or the 1/2" tubing (Figure 1B-22). Liquid flows from the 1/16" tubing into 1/2" tubing, then passes from the 1/2" tubing into the injection wells using reducing couplings (Figure S1D; Table S1, #23) to secure the tubing to the top of the wells.

The injection manifolds were mounted high enough to allow for continuous downward flow through the 1/2" tubing toward the injection wells; this ensures liquid won't back up or collect in the 1/2" tubing, which could lead to inconsistencies in the flow (Figure S1A and B). The following details provide one example of a successful way of mounting and stabilizing the system. Other injection experiments or sites may require some alterations to this method. The injection manifolds were installed ~1 m above the top of the well casings (Figure S1A). Angle brackets (Figure 1B-14) were mounted to each side of the horizontal

PVC plate (Figure S1B and Figure 1B-16) to which the manifolds had been affixed (hereafter called the upper horizontal PVC plate) and were attached to 10' aluminum strut channels (Figure 1B-9). For added stability, a second horizontal PVC plate (lower horizontal PVC plate) was bolted to the top of the well casing of the middle injection well nest (Figure S1E) and was also fitted with angle brackets that connected to the 10' aluminum strut channels. The strut channels were sunk approximately 1 m into the ground; this gave support and kept the injection system stable while the pump was running. For another level of added stability, bolts were tapped into the sides of the well cap (Figure S1E; Table S1, #10) to brace the well cap against the well casing. A 3" (7.6 cm) diameter hole was cut into the top of the well cap of the middle injection well nest and lower horizontal PVC plate (Figure S1E) to allow room for tubing to pass to the top of the wells.

To level the injection system, which helps maintain even distribution of fluids to each outlet port, a hole for a 3/8" threaded rod (Figure 1B-15) was tapped into each corner of the upper and lower horizontal PVC plates. Locknuts (Figure 1B-12) securing the 6-foot rods to the plates were adjusted until the upper horizontal PVC plate was level as measured by two horizontal-mount levels (we recommend a bull's eye level for greater accuracy, Figure 1B-18, 19, 20). After leveling, the plates were screwed down (Figure 1B-10, 11, 12, 13, 14) into the aluminum strut channels (Figure 1B-9) for greater stability.

This system is easily adaptable to other field sites; the number of injection points can be adjusted by choosing a manifold with 4 or 8 outlets (or a combination thereof, linked with a hex nipple and unused outlets blocked with hex hollow plugs). The key features to successfully using the system are (1) keeping the manifold mounted high enough that liquid always flows downward through the 1/2" tubing toward the injection wells, (2) precisely leveling the manifold, (3) ensuring enough stability (by mounting to aluminum strut channels, etc.) that the pulsations from the pump or disturbances from environmental conditions do not significantly alter the leveling during the experiment, and (4) ensuring that the 1/16" tubing has the same maximum height and end point height for each port.

It may be necessary to include a venting system if the liquids being pumped are prone to degassing; formation of bubbles can lead to air being trapped within the manifold or the 1/16" tubing. Trapped air can result in uneven distribution of liquid to the outflow ports. The liquids and tracers used in these experiments did not degas so a venting system was not used. To accomplish venting, one could insert pipe-to-tubing adapters (1/4" pipe to 1/2" ID tube) with a length of 1/2" tubing in the ports at the outer edges of the manifold. The 1/2" tubing should be secured with the opening upwards; therefore, gasses can escape.

Results and Discussion

During the pilot experiment, the flow rate was measured 20 times over 13 weeks. Between 4 and 12 of the ports were measured each time; it was not feasible to measure the ports going to the middle wells, to which the injection system was mounted, due to the relatively small clearance between the tubing and the edge of the well cap opening. Two injection rates were used during the injection experiment; the injection rate is proportional to both the speed and stroke settings of the pump. The speed setting has units of strokes/unit-time. The number

corresponds to strokes/min within 10% error. The stroke setting is related to how much the pump diaphragm moves with each pulse, with the number corresponding to percent of maximum displacement. Though we only present results for use of the system with a chemical metering pump, the concept of the system should still be valid with other pump types.

In Phase I, the total flow rate was 0.27 L/min and stroke and speed of the pump were set at 83 and 50, respectively. There were 46.5 strokes/min and average volume per stroke was 5.8 mL. The average volume per port per minute was between 17.4 and 18.5 mL in Phase I with a relative standard deviation (RSD) < 4% (Figure 2). This data is also illustrated in tabular format in the online Supporting Information (Table S2). Over the course of Phase I (34 days), the average volume per port showed an incremental increase from 17.4 to 18.5 mL per minute, (6% over 34 days). The slight increase over time could have been caused by loosening of the pump diaphragm as the pump was breaking in; this was the first time the pump was used for any significant period of time (i.e., >8 hrs). In Phase II, the total flow rate was 0.56 L/min and stroke and speed of the pump were set at 83 and 95, respectively. There were 94 strokes/min and average volume per stroke was 6.0 mL. The average volume per port per minute was between 36.7 and 38.1 mL with a RSD < 3% (Figure 2). This data can also be found in tabular format in the online Supporting Information (Table S2). There was no systematic change in flow rate over the 56 days of Phase II. The results from flow monitoring during the pilot experiment show that there is even distribution of liquid between the different outflow ports throughout the three months of the injection.

Additionally, samples were obtained via peristaltic pump from within the well bore of one of the injection wells during Phase I and Phase II of injection. Samples were analyzed by ion chromatography (Dionex ICS-2000). During Phase I, the tracer and oxalic acid concentrations measured in the well bore were 7% and 2% different, respectively, compared with the influent concentration on that day. During Phase II, the tracer and oxalic acid concentrations measured in the well bore were 2% and 14% different, respectively, compared with the influent concentration on that day. This suggests a high degree of consistency between injected concentrations and well bore concentrations and thus sufficient mixing within the well bore.

Following the injection experiment, the robustness of the system was tested. The effect of stroke, speed, and tubing stiffness were evaluated. The stroke and speed were varied and tested with the bulk of the 3/8" flexible PVC tubing from the pump to the tube fitting tee replaced with 1/4" braided reinforced tubing to examine whether tubing size and wall strength would impact the flow results. For these tests, 5 or 15 outflow ports were measured (one from each well nest or all outflow ports). With the pump speed set at 95, the relative standard deviations for the average volume per port per minute were less than 3% for both tubing types for the three stroke settings tested - 83, 60, and 30 (Table 1). Except for the tests with pump speed at 95 and stroke at 30, the volumes per port per minute were significantly different for the two tubing types ($p < 0.05$). The discrepancy could indicate that using more rigid tubing leads to slightly larger flow output; the rigid walls of the tubing could cause less dampening of each pulse of the chemical metering pump.

To examine how changes in pump speed would impact distribution of solution among the outflow ports, the stroke was set at 60 and the speed varied (Table 1). With the 3/8" tubing, the speed was set at 70, 40, and 30 in successive trials. Percent relative standard deviation for average volume per port per minute was <5% for speeds of 70 and 40. However, when the speed setting was reduced to 30, there was greater variation in the distribution of liquid; relative standard deviation was 13.9%. At slower speeds it became evident that air was pulled back into the 1/16" tubing between each pulse of the pump. The horizontal-mount levels used in the field design were not sensitive enough for extremely precise leveling; therefore, air was pulled back further into the 1/16" tubing on the left side of the injection manifold than on the right. This issue only seems to be a problem at the lower speeds; however, this is the reason we recommend using a bull's-eye level (Table S1, #18, 19, 20) rather than horizontal-mount levels.

Using the 1/4" braided, reinforced tubing, speeds of 60, 50, and 40 were tested (stroke = 60 in each case). We again observed that at lower speeds the relative standard deviation for average volume per port per minute would increase; for speed settings of 60 and 50 the relative standard deviations were <8%. However, when the speed setting was lowered to 40, the relative standard deviation climbed to 20.8%. Note that the relative standard deviation exceeded 10% with the speed setting at 30 with the 3/8" tubing and 40 with the 1/4" braided, reinforced tubing. A possible reason for this difference is that the 1/4" braided, reinforced tubing has a smaller opening and less flexible walls, which could lead to stronger pulses from the pump (the more flexible walls of the 3/8" tubing could dampen the pulses). Stronger pulses would also lead to more air being pulled back into the 1/16" tubing between pulses. Therefore, very precise leveling becomes more important when slower speed settings are used as well as smaller diameter, more rigid tubing.

Conclusions

An injection manifold system was designed that uses a single pump to evenly distribute flow to 15 ports using inexpensive and readily available materials. Except for one metal spring, the system is made of plastic and allows the injection of chemically aggressive fluids. Injected fluids do come in contact with air due to venting in the system. Over the course of a three-month experiment during which the system was used, even flow distribution was maintained across the injection manifold. Relative standard deviations for average flow rate were <4% for both phases of the experiment (Phase I = 0.27 L/min total flow, Phase II = 0.56 L/min total flow) throughout the three-month experiment. This injection system is adaptable for varying numbers of injection points and can be used for a wide array of multi-well injection scenarios.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

(A) and (B) show schematic diagrams of the injection system. The parts are listed in Table S1 in the online Supporting Information. Blue arrows indicate flow direction. Briefly, the liquid flows from the pump through 3/8" tubing (1A-7) and is split by a tube fitting tee (1A-8). Liquid then passes through a short length of 3/8" tubing on either side of the manifolds; liquid flows through tube-to-pipe elbows (1A-6) to the manifolds (1A-5) and up through the tube-to-pipe adapters (1A-3) to the 1/16" tubing (1A-1). The 1/16" tubing is threaded through holes in the vertical PVC plate (2B-16) and through holes cut in plastic plugs (1B-17), stopping at the bottom of the thru-wall adapters (1B-21). Liquid passes from the bottom of the 1/16" tubing into 1/2" tubing (1B-22), which is connected to the thru-wall adapters and leads to the top of the injection wells.

Figure 2. Flow Rates During Phase I and Phase II of Injection

Flow rates during the Vineland injection. The error bars show 1 standard deviation above and below the average value. During Phase I, the total output was 0.27 L/min. The pump settings were Stroke = 83, Speed = 50; for these settings, stroke/min = 46.5 and average mL/stroke = 5.8 mL. During Phase II, total output was 0.56 L/min. The pump settings were Stroke = 83, Speed = 95. For these settings, stroke/min = 94 and average mL/stroke = 6 mL.

Table 1**Flow Tests with Varying Stroke and Speed**

Stroke	Speed	Total rate (L/min)	Average volume per port per minute (mL)	Standard Deviation	% RSD	N
83	95	0.55	36.8	0.25	0.68	5
60	95	0.42	28.0	0.64	2.28	15
30	95	0.24	15.8	0.47	2.97	5
60	70	0.29	19.5	0.52	2.67	15
60	40	0.18	11.8	0.50	4.26	5
60	30	0.13	8.8	1.21	13.9	5

In the following tests, the bulk of the tubing from pump to the tube fitting tee was decreased in size to 1/4" and was braided, reinforced (McMaster part # 52375K12).

83	95	0.56	37.6	0.37	0.99	5
60	95	0.43	28.8	0.66	2.30	15
30	95	0.24	16.2	0.45	2.76	5
60	60	0.27	18.1	0.58	3.18	5
60	50	0.23	15.3	1.09	7.15	5
60	40	0.18	12.0	2.49	20.8	5

N= Number ports tested; %RSD= % Relative Standard Deviation