Visualizing Numerical Flow Simulations of Karst Aquifers

Hervé Sanglard
Computer Science Department
herve.sanglard@info.unine.ch

Michael Hauns
Hydrogeology Center
michael.hauns@chyn.unine.ch

University of Neuchâtel
Switzerland

Abstract

The use of the visualization platform ZoomIn which was developed to satisfy the double goal of intuitivity and extensibility is demonstrated on the example of visualizing flow and tracer transport simulations in the conduits of a karst aquifer.

Keywords: scientific visualization, visualization platform, computational fluid dynamics, hydrogeology, karst aquifers

1 Introduction

Scientific visualization consists in representing results obtained from measures or produced by numerical simulation. Traditionally, visualization was done by people whose education allowed them to master the scientific context and the computer problems related to visualization simultaneously. But the price of nowadays' graphical workstations brings them to the desk of scientists with very different backgrounds, who do not always want to spend time for developing computer tools. This causes a demand for visualization environments which which have to satisfy new requirements:

- Visualization tools have to be provided to users who *do not master all the technical aspects* that play a role. This is typically the case of people with a background in natural sciences.

- Also in the classical exact sciences, a *division of labour* is taking place, because the scientist that we shall call the *end user* wants to concentrate on his main research and cannot spend too much time on tooling problems.

The platform ZoomIn was developed with these goals in mind. Details about the concept of ZoomIn can be found in [6]. In the present paper ZoomIn is applied to numerical simulations of a hydrogeologic problem.

From the modeling scientists' point of view, the specifications for visualization of this problem are:

- identification of the general flow pattern; a quick analysis of this is desired at an early stage of the simulation because it helps to refine it;

- appropriate representation of time dependent data to understand the transport processes;

- a special instrument to relate spatial and temporal evolution more closely is desired. A concentration graph glyph fulfills that requirement and will be described in more detail later;

- last but not least, it is important to have a working environment that makes possible intuitive manipulations of the graphical representations and precise selections of regions of interest and points of view in order to recognize patterns.

2 Problem Description

2.1 Hydrogeologic Problem to Solve

Hydrogeologists use the response of an aquifer (underground water reservoir) to a natural or artificial input signal to gain information about its characteristics. Dye tracer is an often-used artificial input, and in this study we are interested in the behaviour of karst aquifers where major flows paths are in fissures and fractures up to metric dimensions. Figure 1A shows a schematic view of a karst aquifer. Water infiltrates by the epikarst zone and flows through conduits on top of the saturated zone towards a spring.
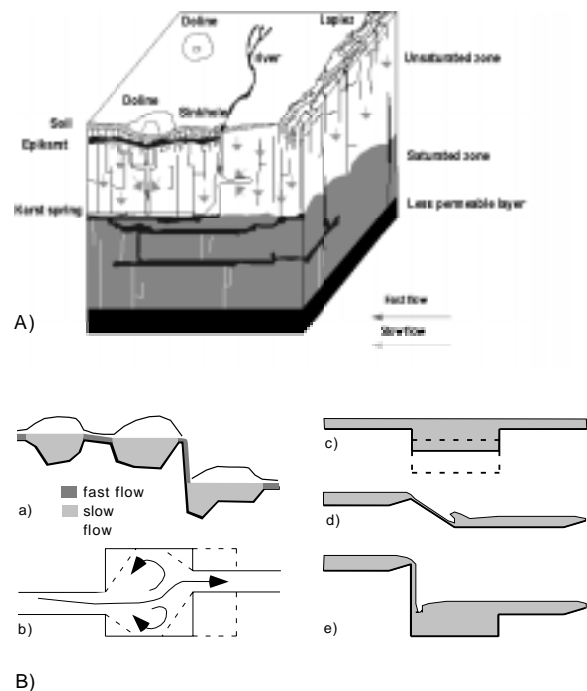

Figure 1: Karst aquifer

These conduits may be imaged as a sequence of 'storage' and connection elements, with irregular shapes in which the flow often changes from stagnant to fast (fig. 1Ba). Field studies in the underground river Milandrine (JU, Switzerland) have shown that a measurable tailing effect of a micro tracing breakthrough curve can be induced by the conduit geometry, namely by large pools (fig. 1Bb). Therefore a detailed study of the flow in such an irregular conduit has been undertaken. A laboratory scale model of a pool was built, and the flow within the domain of interest is simulated with a computational fluid dynamics model [3].

2.2 Numerical Method

The flow in a conduit enlargement or pool is simulated with a 3D flow solver based on a finite volume method and a block structured grid with a resolution of 80 x 75 x 4 nodes. The physical dimensions of the pool are approximately 1m x 1m, with an entry and exit channel each 1m long. The waterdepth is known from the outflow condition and therefore a rigid lid approximation for the top boundary can be used. First, a steady state flow solution is computed. Then dye tracer is injected during 2 seconds, and the transport is calculated with an additional scalar transport equation on the velocities of the first solution.

The simulation covers 1000 seconds and is carried out with 10'000 time steps of 0.1 second. Every 50th time step is stored is the solution file which has a size of 60 MB. It is located on the file system of the machine hosting the visualization platform.

3 Visualization Platform

In order to visualize the dataset generated by the numerical simulation, a platform called ZoomIn was used. This platform has been developed with two goals in mind :

- to provide an intuitive visualization platform for time dependent three dimensional simulations;

- to make the integration of new visualization techniques quick and easy.

To fulfill this double goal, a definition proposed by Haber and McNabb in [2] about *visualization objects* was refined in [6]. The core architecture of the platform has been built around a hierarchy of three *visualization objects* modeling three stages of the visualization pipeline.

- Mapping of data : An *AVO* (Abstract Visualization Object) is a *function* which maps part of the data onto a geometric object with certain properties; this application is controlled by *parameters*, whereas the data on which the AVO acts is called *source*. The isosurface is an example of such an AVO, the source being a scalar field, the parameter the threshold.

- Conceptual representation : A *CVO* (Concrete Visualization Object) is a 3D object which exists only in the conceptual world of the user. The "semi-transparent isosurface of the temperature field for the value $16^{\circ}C$ " (with the corresponding color, reflectance and texture) is an example of a CVO. A CVO thus encompasses attributes including color, transparency, and so on. More formally:

$$\mathrm{CVO} = \mathrm{AVO}(source, parameters)$$

- Graphical representation : A *RVO* (Represented Visualization Object) is the approximation of the (ideal) CVO which is manipulated by the graphical system. Whereas in our example the CVO "semi-transparent isosurface of the temperature field for the value $16^{\circ}C$" has a *smooth surface*, the corresponding RVO is a *polyhedron* which is projected onto the screen.

Thanks to this abstraction, ZoomIn can accommodate the large majority of the techniques which are available in the different packages, be it isosurfaces or cutting planes [1], particle traces, textures, vortex extraction [4], glyphs or icons [5]. The results obtained can directly be exported into pictures, movies and virtual objects (VRML scenes).

From the implementation point of view, the platform does in fact *not know* what the objects it manipulates really are. It can therefore control new AVOs without any need for recompilation, as long as these AVOs comply with a given interface. The platform offers general facilities like manipulations of visualization objects, new-open-save-print-export functionalities, time and view management and copy-cut-paste-undo commands. The user explores the data using all these conveniences and the programmer takes them for free during the implementation of a new visualization object simply by subclassing it from the AVO abstract class.

The region of interest (ROI) is one of the main parameters of the AVO the user has to select to create or to update a CVO. It represents the portion of the spatial domain the user wants to concentrate on. The platform provides *direct* and *indirect* selection mechanisms. The *direct* selection mechanism is available through manipulators controlled by classical devices like a mouse or a space ball. In order to give precise values to distances or positions, *indirect* means like dialog boxes or sliders are required. This is particularly important as soon as the visual clutter reaches a certain level: direct means then lead to long and troublesome manipulations.

The most important AVOs developed for this study are :

- cutting plane and isosurface to express turbulence and to visualize the propagation of the tracer;

- simple 3D conical glyphs expressing the direction and the magnitude of the velocity field;

- a glyph representing the evolution in time of the tracer by a graph at the position of interest;

- streamlines to make the detection of vortices easy;

- an AVO with a transparency property representing the bathymetry to help the user during exploration in 3D space.

In order to access to the data, the interface of ZoomIn was defined as a *set of methods of a data server* rather than by data formats; this makes the platform independent of the data source, which can then be implemented as a set of files or an area in shared memory, either local or remote. The task of this data server is to supply the visualization environment with raw data and with derived data: raw data are the data directly produced by the numerical simulation program, derived data those produced by the evaluation of expressions based on raw data, like the vector norm or the sum of two scalars. A specific dataset driver has been developed for this study using *The Visualization Toolkit* and easily integrated into the platform through a shared library.

4 Flow and Tracer Visualization

The time required to customize ZoomIn for this study to integrate the necessary visualization AVOs was about two weeks. Thanks to the design of the platform, most of the AVOs developed for a previous investigation in the field of oceanography could be reused and extended. This is a short time if one takes into consideration that the environment provided for the hydrogeologist is intuitive, customized and interactive and powerful enough to visualize the dataset with a reasonable latency on a SGI Octane with one R10000 processor at 195 MHz.

4.1 Major Flow Characteristics

The first objective is to recognize the general pattern (i.e. central flowpath and recirculation zones) of the obtained flow solution. To get a general overview a cutting plane of the speed distribution was created. The colorscale is between blue (0.0 m/s) and red (0.08 m/s). Coarsely gridded velocity arrows are superposed to indicate the global flow direction (fig. 3).

To recognize the shape and location of the principal eddy a second set of arrows with the same length scaling but with a finer sampling is superposed in a region of interest covering the eddy (fig. 3). In the upper left corner of the pool a smaller eddy is turning in the opposite sense. It is visualized with a still finer spacing of arrows. Due to the smaller velocity prevailing here, the arrow length scale was chosen four times larger and the base diameter smaller. The arrows in this region of interest were colored in red to distinguish them from the other arrows with a different scaling. Figure 4 shows the small eddy in detail.

Vortices smaller than the computational grid size down to the Kolmogorov scale cannot be resolved with the available computing power, but are however important for the turbulent dispersion of tracer. The turbulent kinetic energy K is a measure for their intensity. Figure 5 shows a plane cut at z=0.02 colored with the turbulent kinetic energy. An isosurface of K is superposed to emphasize the 3D structure of the zones of high turbulence. One of them is situated between the inflow jet and the main eddy; this zone is where tracer will be dispersed to the stagnant zone. In this picture some velocity arrows are added to help to show the main eddy to those observers who are less familiar with the problem.

4.2   Tracer Transport

In general an isosurface gives a good 3D impression of the tracer density. However in the present problem, the turbulent eddy structure is mainly in the xy plane therefore a cutting plane was choosen; on the one hand it contains the essential information about the plume shape, on the other hand it gives more information about the distribution inside the plume than an isosurface. Figure 7 shows the tracer plume at times 5, 25, 60, 115, 235 and 300s respectively. The colormap is automatically adjusted to the minimum and maximum at each time step because, due to diffusion, the concentration decreases strongly during time.

The plume enters the pool (5s) then passes along the wall (25s). The small eddy in the lower left corner is not yet filled, and on the backside of the plume, the clear water jet from the entrance is visible. When reaching the exit, the plume divides in two parts; the main packet and the portion that will give the tailing later. Now some tracer is also turning in the lower right corner. After 115 seconds the core of the trapped dye has completed one tour and starts to wash back into the main flowpath. After 235 seconds it has completed a second tour. Now a visible amount of dye stays in the small eddy shown in figure 4. Note that the dye reaches the center of the eddy only very slowly. After 300 seconds the center of gravity of the trapped dye plume can still be clearly distinguished.

In addition to this, one would like to see the graph concentration as a function of time $(C(t))$ at different points to have a more quantitative information. An interactive *glyph probe* that updates a $C(t)$ graph for the desired location was developed. Glyphs were put on several locations on the background of the tracer concentration cut at time=275s (fig. 6). The glyphs represent temporal evolution at the respective point between 0 and 300 seconds. On the glyph at the pool entrance, the rectangular form of the input signal can still be seen, while on the lower right glyph there is already some dispersion. On the outer orbit of the central eddy the passage of the plume core leaves multiple peaks while the concentration in the center rises very slowly. Part of the breakthrough curve at the exit (from 155s to 1000s) to is zoomed out in figure 2; the tailing is composed of several peaks which originate from repeated contact of the plume core in the eddy with the main flowchannel. Note that the scale of the glyphs is automatically adapted to the minimum and maximum concentration throughout the time at the position of the glyph.

Animation in time is an important tool to understand the dynamics of the plume passage. Using ZoomIn it is possible to build
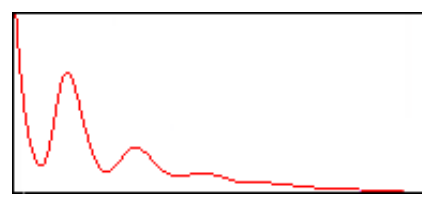

Figure 2: Concentration glyph

keyframe animation from the individual time steps and record it automatically into a movie file.

5   Conclusion

The new visualization platform ZoomIn was applied to a numerical solution of a hydrogeologic problem. The main goals were analysis of the steady state solution for the velocity and turbulence field and the transient simulation of the passage of a dye tracer plume. In case of the flow solution vortex structures that are more than an order of magnitude apart could be recognized and located in the general flow situation using regions of interest with well adapted arrow grid spacing. For the tracer plume passage both the overall evolution of the plume shape in time and a quantitative analysis of the tracer concentration at some points are important.

A sequence of snapshots in time with an automatically adapted colormap allows a good understanding of the plume dynamics.

The glyphs prove very useful in relating spatial and temporal evolution of the tracer.

Usage of the platform is very intuitive but technical requirements lead to intensive computations. Most of the figures in this paper were produced within a reasonable latency time; however further work to optimize the performance of the platform and the data server is necessary.

References

[1] Richard S. Gallagher. Scalar visualization techniques. In *Computer Visualization, Graphics Techniques for Scientific and Engineering Analysis*, pages 89–127. CRC Press, 1995.

[2] R. B. Haber and D. A. McNabb. Visualization idioms : A conceptual model for scientific visualization systems. In *Visualization in Scientific Computing*, pages 74–93. IEEE Computer Society Press, 1990.

[3] M. Hauns, P.-Y. Jeannin, and F. Herrmann. Tracer transport in undergound rivers in karst: tailing effect and channel geometry. In *Bulletin d'Hydrogéologie Num. 16*. CHYN, Université de Neuchâtel, Switzerland, 1997.

[4] David A. Lane. Scientific visualization of large-scale unsteady fluid flows. In *Scientific Visualization, Overviews-Methodologies-Techniques*, pages 125–145. IEEE Computer Society, 1997.

[5] Frank J. Post, Theo van Walsum, Frits H. Posts, and Deborah Silver. Iconic techniques for feature visualization. In *Proceedings Visualization '95*, pages 288–295. IEEE Computer Society, 1995.

[6] Hervé Sanglard and Hans-Heinrich Nägeli. An end user oriented platform for scientific visualization. In *Proceedings Information Visualization '97*. IEEE Computer Society, 1997.
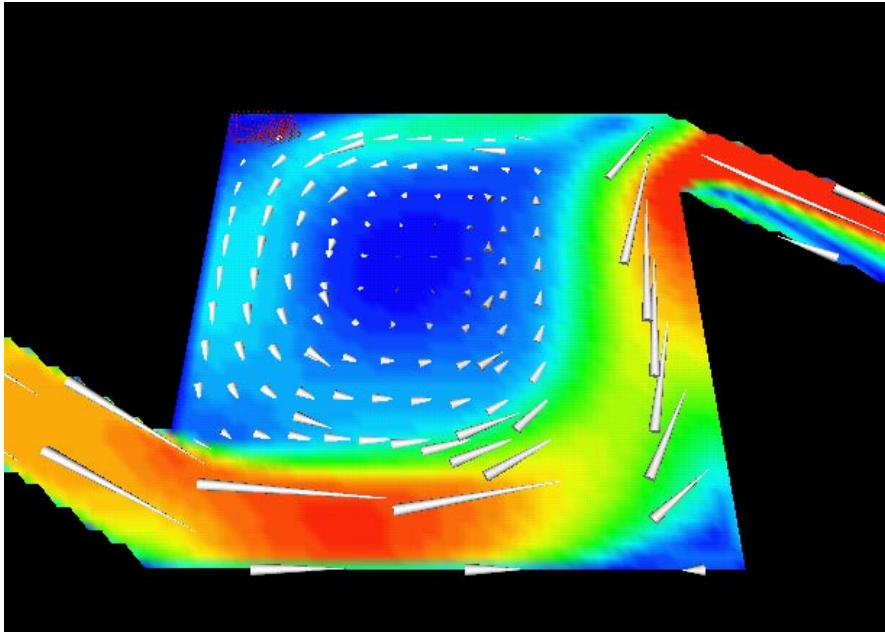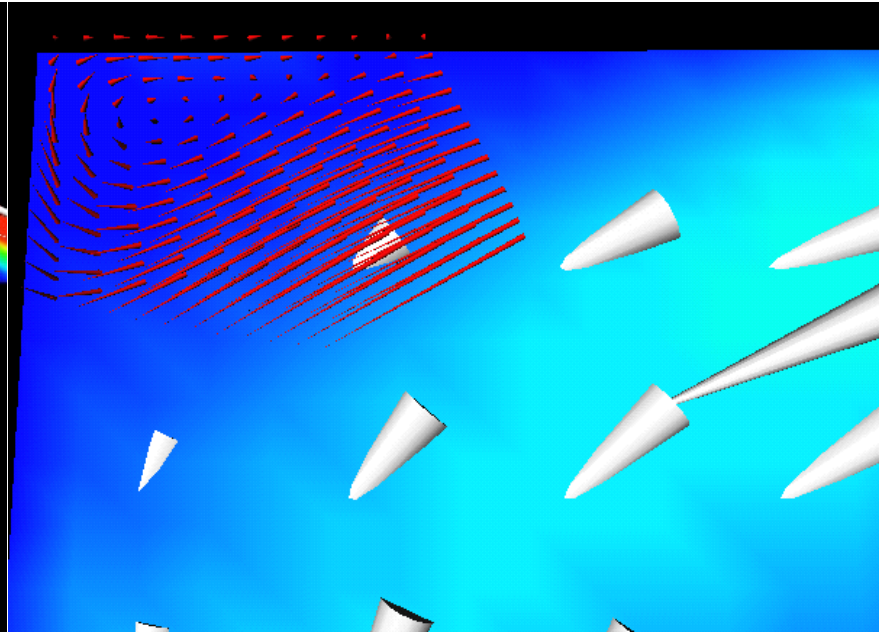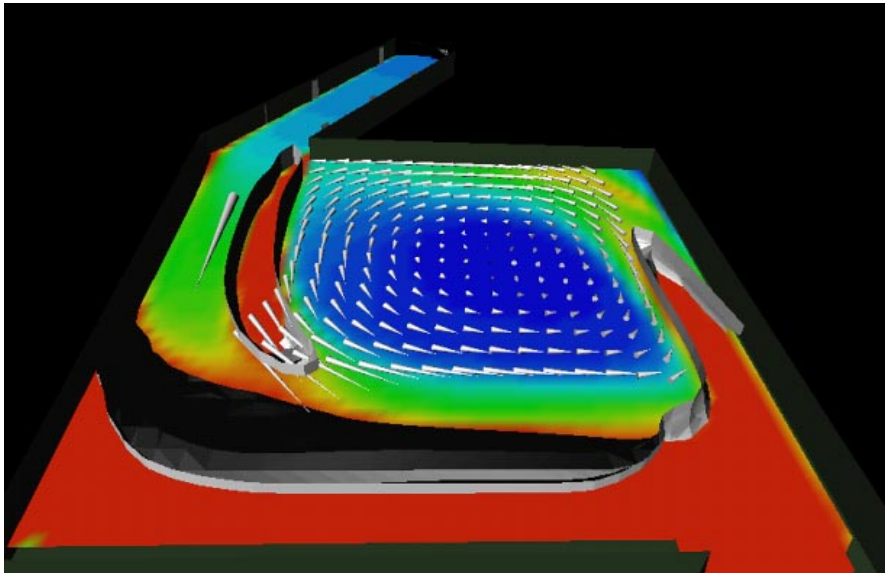
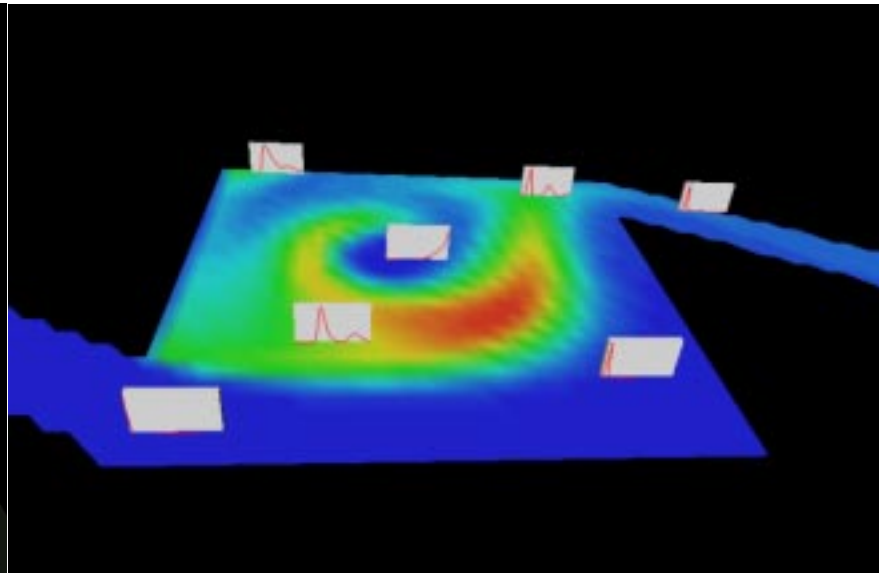Figure 3: Cutting plane of speed and principal eddy

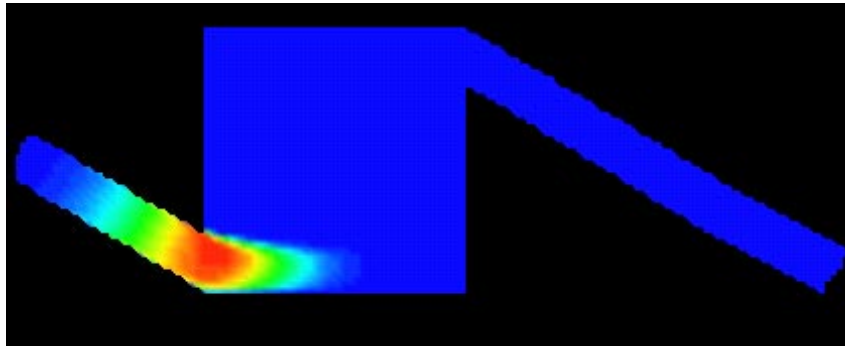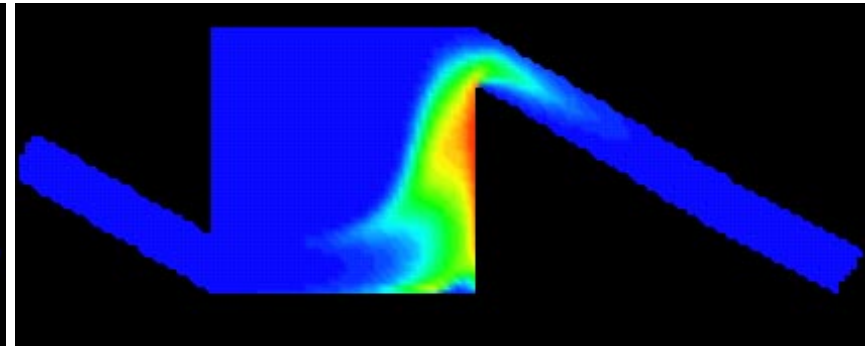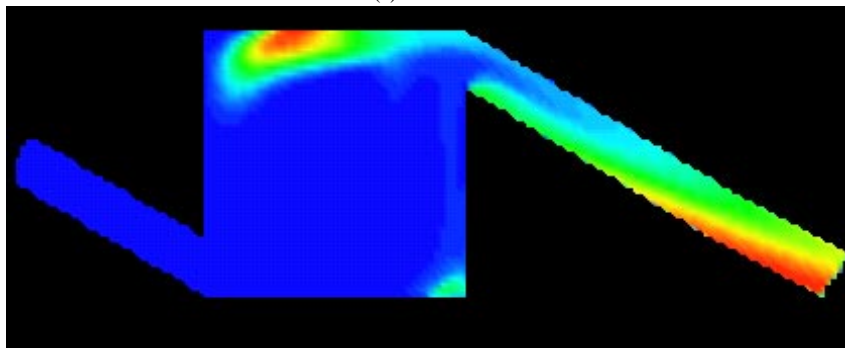
Figure 4: Small eddy in detail

Figure 5: Turbulent kinetic energy
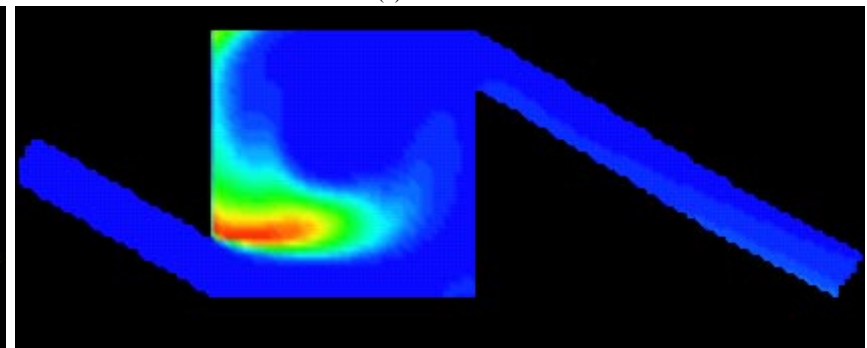

Figure 6: Concentration glyphs
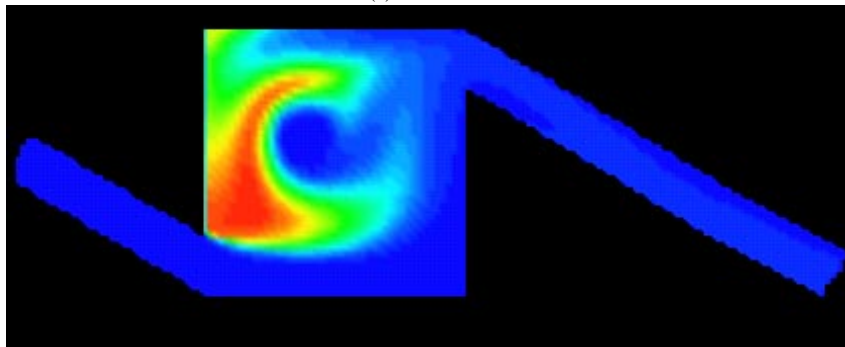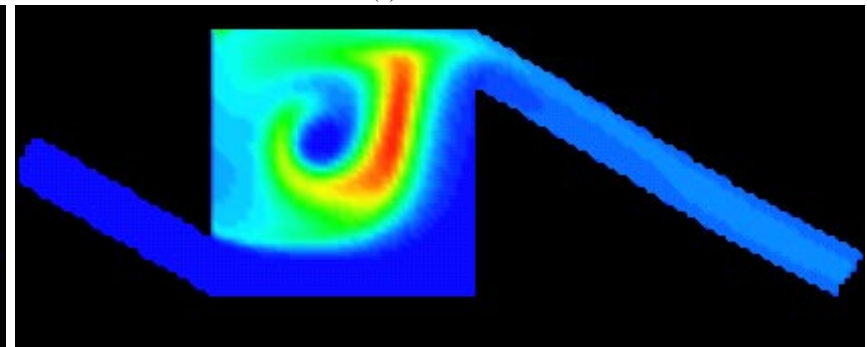
(a) 5 seconds

(b) 25 seconds

(c) 60 seconds

(d) 115 seconds

(e) 235 seconds

(f) 300 seconds

Figure 7: Tracer plume