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# External Memorandum

**To:** Distribution

**cc:** Mr. Roger W. Blair, PB Energy Storage Services, Inc.
Project Central File 1800-23 — Category C

**From:** Dr. Joe L. Ratigan
Consultant to PB ESS
PB Energy Storage Services, Inc.
P.O. Box 725
Rapid City, SD 57709

**Date:** August 29, 2012

**Subject:** 2012 Napoelonville Salt Dome Subsidence Report

Enclosed is a copy of the report (PB-0348) titled *Precision Level Surveys and Subsidence Analysis, Napoleonville Salt Dome, Grand Bayou, Louisiana, 2012 Report to Napoleonville Operators.* I intend on providing an on-site presentation of the subsidence monitoring results in 2012. If you have any questions, please let me know. Thank you for the opportunity to develop this report.

JLR:krl

Enclosure

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# PRECISION LEVEL SURVEYS AND SUBSIDENCE ANALYSIS, NAPOLEONVILLE SALT DOME GRAND BAYOU, LOUISIANA 2012 REPORT TO NAPOLEONVILLE OPERATORS

Topical Report PB-0348

*prepared for*

Napoleonville Salt Dome Operators
Grand Bayou, Louisiana

August 2012

PBEnergy Storage Services, Inc.
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# PRECISION LEVEL SURVEYS AND SUBSIDENCE ANALYSIS, NAPOLEONVILLE SALT DOME GRAND BAYOU, LOUISIANA 2012 REPORT TO NAPOLEONVILLE OPERATORS

Topical Report PB-0348

*by*

Joe L. Ratigan

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16285 Park Ten Place, Suite 400
Houston, Texas 77084

*prepared for*

Napoleonville Salt Dome Operators
Grand Bayou, Louisiana

August 2012

# FOREWORD

This report describes subsidence rates at the Napoleonville salt dome determined from annual precision level surveys performed since early 1995. The subsidence results from geomechanical phenomena including the gradual salt creep closure of the underground solution-mined wells in the salt dome. Beginning in 2001, the Global Positioning System (GPS) survey (used to establish an elevation reference) was discontinued as it is believed that the amount of annual subsidence is significantly less than the estimated accuracy of the GPS survey. In 2009, evaluation of horizontal ground strains was incorporated into the subsidence analysis.

This report was developed by Ratigan Engineering & Consulting LLC under subcontract to PB Energy Storage Services, Inc.

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# 1.0 INTRODUCTION

In 1994, the brine mining and underground hydrocarbon storage operators at the Napoleonville salt dome in Louisiana commissioned the development of a subsidence monitoring program at the Napoleonville salt dome. Subsidence at the Napoleonville salt dome is determined by comparing the results of successive precision level surveys of a series of benchmarks. The benchmarks at Napoleonville consist of LPG and natural gas storage wellheads, brine production wellheads, a saltwater disposal wellhead, water wells, concrete surface benchmarks, and a series of benchmark monuments initially designed and installed in 1994.[1]

Since 1994, several benchmarks have been added and some of the original survey benchmarks are no longer in the benchmark network. During 1997, OXY Well No. 9 on the Occidental Co. property was completed and has been included in surveys since 1998. The current total number of each benchmark type is shown in Table 1-1. Benchmarks removed from the network are also shown in this table. Water wells and most concrete benchmarks have been removed from the network because of their lack of stability. In 2002, a deep, off-dome reference benchmark was added to the network. The new reference benchmark is called Dow Monument 20. In 2001, Bridgeline added four benchmarks in the vicinity of their gas well, and Promix plugged a well (2A) in 2002. In 2004, Gulf South drilled the Magnolia No. 1 well. This well is now owned and operated by Dow. Table 1-2 lists the benchmarks that have been "disturbed" or destroyed since the network was installed. Additionally, four benchmarks (Dow Monuments 14, 15, 17, and Enron Storage Well Monument 4)[2], are under water. All four of these benchmarks were surveyed in 2012 following a special request to the surveyor.

Beginning in 2009 [Ratigan, 2010], the subsidence report includes an analysis of the approximate horizontal strain rates that develop as a result of the vertical ground subsidence. This horizontal strain analysis is provided in Chapter 5.0.

The Napoleonville benchmark network covers the terminal properties owned or operated by Dow Chemical; PB Energy Storage Services, Inc.; Texas Brine (formerly owned or operated by Vulcan); Bridgeline (formerly owned or operated by Enron); Georgia Gulf;[3] Union Carbide; Enterprise (formerly owned or operated by Shell Oil);[4] Promix LLC; and Crosstex (formerly owned or operated by El Paso Field Services (formerly owned or operated by Enron)). Annual precision level surveys of this network were performed from early 1995 through 1999 by Morris

[1] Water wells and most concrete surface benchmarks are not used to monitor ground subsidence in this monitoring network as of 2000.

[2] Currently owned by Bridgeline.

[3] Operated by Texas Brine.

[4] Operated by Acadian Gas.

P. Hebert, Inc. of Houma, Louisiana. Surveys in 2000 through 2012 were performed by C. H. Fenstermaker & Associates, Inc., Lafayette, Louisiana. The purpose of this report is to document the latest level survey, which was performed in August 2012, and to report the measured and calculated subsidence rates. Earlier surveys were previously documented by Nieland and Ratigan [1996], DeVries [1996], Nieland [1997; 1998], and Ratigan [1999; 2000; 2001; 2002; 2003; 2005a; 2005b; 2008; 2010; 2011; 2012].

**Table 1-1. Subsidence Survey Benchmarks at the Napoleonville Salt Dome**

| Benchmark Type | Number of Benchmarks as of December 2010 |
|---|---|
| Storage and Brine Production Wellheads | 51 |
| Saltwater Disposal Wellheads | 1 |
| Water Wells | — |
| Concrete Benchmarks | 1 |
| Installed Benchmarks | |
| GPS/Reference Monuments | 5 |
| Standard Monuments | 32 |
| **Total** | **90** |

**Table 1-2. Lost or Destroyed Benchmarks in the Napoleonville Subsidence Monitoring Network**

| Benchmark | Year Lost or Destroyed |
|---|---|
| Dow Monument 11 | 1999 |
| Dow Monument 12 | 2004 |
| Dow Monument 13 | 2004 |
| Dow Monument 16 | 2004 |
| El Paso Monument 5[(a)] | 2003 |

(a) El Paso Facility is now owned and operated by Crosstex.

# 2.0 LEVEL SURVEY BENCHMARK NETWORK

Level survey benchmarks at Napoleonville currently consist of LPG and natural gas storage wellheads, brine production wellheads, a saltwater disposal wellhead, one concrete benchmark, and the installed benchmark monuments. The elevations of the concrete benchmark will continue to be reported; however, because it may be susceptible to shallow soil movement associated with temperature and moisture changes, this elevation is not included in the subsidence analysis. Measurement of water well elevations was discontinued in 2001.

## 2.1 BENCHMARK LOCATIONS

The North American Datum (NAD 27) Louisiana state plane coordinates for each of the benchmarks as determined by the surveyor are listed in Chapter 3.0.

## 2.2 INSTALLED BENCHMARK DESIGN

A schematic illustration of the installed benchmark monuments is shown in Figure 2-1. The depth of the benchmark (approximately 36 feet) is similar to other installations and is expected to eliminate shallow soil movement associated with temperature and moisture changes. These benchmarks are referred to in this report as installed benchmark monuments. The design for the Global Positioning System (GPS) benchmark monuments is similar with the exception that they were driven to refusal and attained depths between 70 feet and 100 feet.

## 2.3 NETWORK DESIGN

The subsidence network at Napoleonville was designed to enable measurement of the vertical ground movement occurring at the surface. This vertical ground movement will occur principally because of the gradual creep closure of the storage caverns and may be affected by other regional geomechanical or geohydrological phenomena[5]. The benchmark spacing at Napoleonville is not uniform. More benchmarks are generally placed over regions with larger storage well capacities or regions with a higher density of storage wells.

## 2.4 GLOBAL POSITIONING SYSTEM SURVEYS

The land surface in the Gulf Coast is continually moving and often moving at a variable rate. Reference elevations are difficult to establish with precision. Therefore, the Napoleonville

[5] During the course of the 2012 survey, a sinkhole appeared on August 3, 2012, near the western edge of the dome.

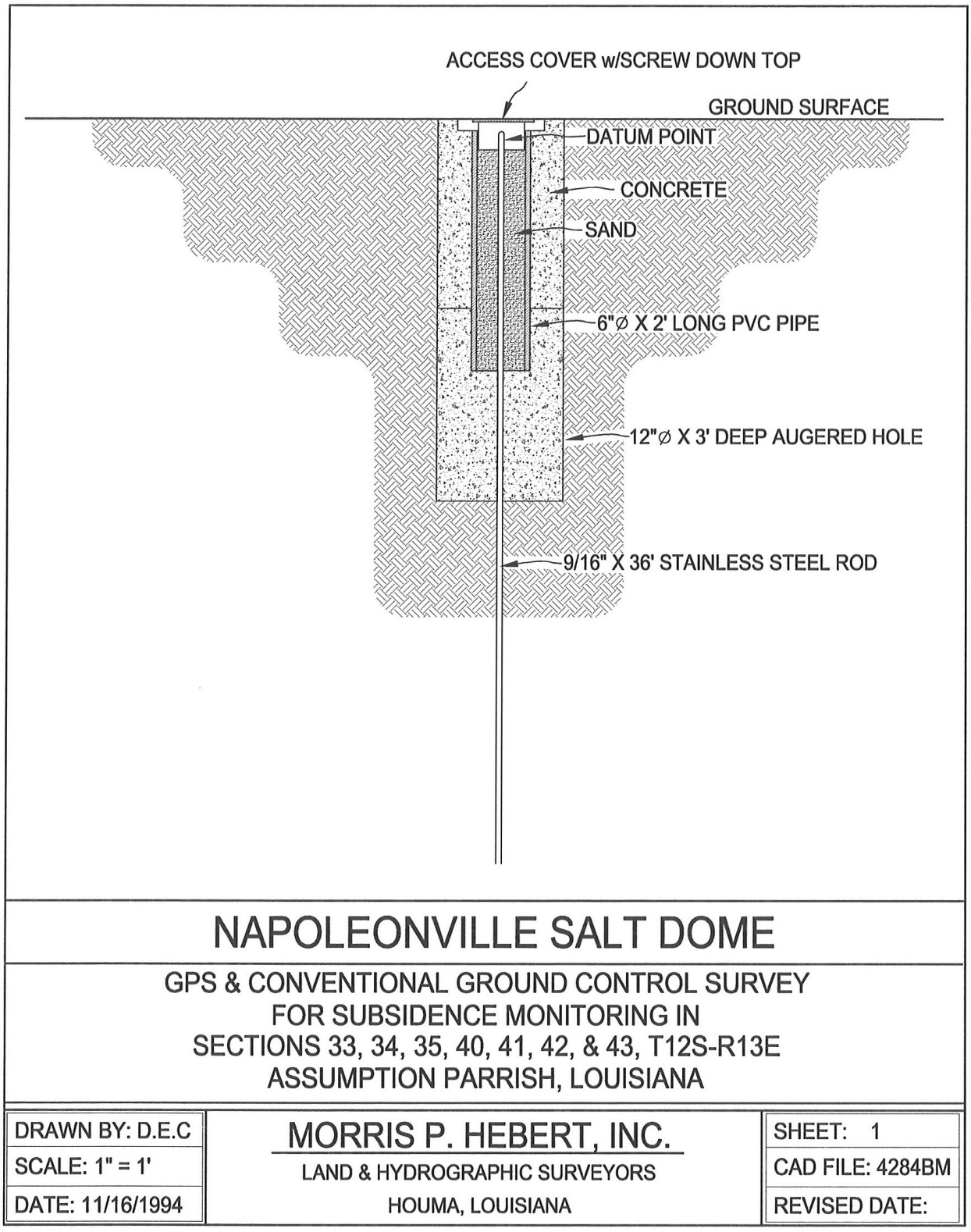


**Figure 2-1.** Benchmark Installation at Napoleonville Salt Dome, Louisiana.

operators commissioned a GPS survey of three reference benchmarks to use in the evaluation of surface subsidence. A fourth GPS reference benchmark was added between the 1996 and 1997 surveys. The benchmark monuments designated for the GPS survey are labeled GPS1, GPS2, GPS3, and GPS4. These monuments were tied to the Louisiana High Accuracy Regional Network (HARN) recently established by the National Geodetic Survey (NGS) with first-order vertical heights and fourth-order ellipsoid values. Three HARN points remote from the Napoleonville salt dome were used in the GPS surveys to determine the elevations of the GPS benchmarks at the Napoleonville site. The three HARN stations are the nearest existing GPS stations which bracket or surround the salt dome. The locations of these reference benchmarks are described in Table 2-1.

**Table 2-1. NGS HARN Stations Included in GPS Surveys at Napoleonville, Louisiana (After Morris P. Hebert, Inc. [1995])**

| Reference Benchmark | Location | Latitude | Longitude | Ellipsoid Height (ft) |
|---|---|---|---|---|
| G 293 | U.S. Corps of Engineers Property; 12 miles south-west of Plaquemine, 4.7 miles northwest of Pigeon, and 1.8 miles south of Bayou Sorrel | 30° 07' 51.212350" | 91° 19' 20.372300" | –65.6299 |
| H P Williams (HPWL) | H. P. Williams Memorial Airport | 29° 42' 40.243240" | 91° 20' 16.165750" | –78.6909 |
| TORI | Thibodaux Municipal Airport | 20° 44' 52.823200" | 90° 49' 36.117300" | –76.5452 |

Beginning with the 2001 subsidence monitoring survey, the GPS survey of the four GPS benchmarks was discontinued. The accuracy of the GPS surveys obtained through 2000 is not believed to justify the expense. As this technology improves, the GPS survey may again be part of the survey program. Beginning in 2001, all elevations reported by the surveyor are with respect to the elevation of GPS1, which is assumed to be 5.906 feet. In this report, all elevations obtained to date have been adjusted to be with respect to GPS1 with an assumed elevation of 5.906 feet.

In 2002, a fifth deep benchmark, located off-dome, was added to the subsidence monitoring network as a "backup" reference benchmark. The benchmark is called Dow Monument 20.

# 3.0 SURVEY RESULTS

Morris P. Hebert, Inc. performed annual GPS and precision level surveys of the Napoleonville benchmark system between 1995 and 1999. C. H. Fenstermaker & Associates, Inc. performed a GPS survey in 2000 and precision level surveys in 2000 through 2012. The chronology of these surveys is shown in Table 3-1. All loops used in the level surveys are required to close within 0.01 foot. The accuracy of the benchmark elevations determined by the GPS surveys performed through 2000 was originally believed to be within 1 centimeter plus 1 part per million times the baseline length. The horizontal location of the benchmarks was determined within 0.5 foot using the Louisiana state plane coordinate system (NAD 27).

**Table 3-1. GPS and Level Surveys Performed by Morris P. Hebert, Inc. and C. H. Fenstermaker & Associates, Inc. at Napoleonville**

| Survey Number | Date Initiated | Date Ended |
|---|---|---|
| 1 | January 4, 1995 | February 1, 1995 |
| 2 | January 29, 1996 | February 9, 1996 |
| 3 | March 6, 1997 | March 21, 1997 |
| 4 | February 3, 1998 | March 6, 1998 |
| 5 | March 2, 1999 | April 29, 1999 |
| 6 | May 31, 2000 | July 26, 2000 |
| 7 | May 30, 2001 | June 26, 2001 |
| 8 | May 1, 2002 | May 16, 2002 |
| 9 | April 1, 2003 | May 13, 2003 |
| 10 | June 30, 2004 | July 23, 2004 |
| 11 | March 30, 2005 | April 15, 2005 |
| 12 | July 24, 2008 | September 15, 2008 |
| 13 | September 28, 2009 | October 16, 2009 |
| 14 | November 1, 2010 | November 15, 2010 |
| 15 | September 26, 2011 | October 10, 2011 |
| 16 | August 1, 2012 | August 11, 2012 |

The horizontal locations (Louisiana state plane coordinates with respect to NAD 27) and the level survey elevations of the benchmarks reported by Morris P. Hebert, Inc. and C. H.

Fenstermaker & Associates, Inc.[6] are provided in previous reports. The surveyed elevations are given by property in Tables 3-2 through 3-10. Table 3-11 contains the level survey elevations of the GPS benchmarks. Previous GPS survey elevations of the GPS benchmarks are reported in Ratigan [2000].

For the storage and brine production wells, a point on the lower portion of the Bradenhead flange is used to eliminate any elevation disturbances resulting from workovers. During the level surveys, the elevation on top of the Bradenhead flange is determined. The Bradenhead flange thickness is then measured ("calipered"), and the elevation of the underside of the flange is then calculated. However, if the lower portion of the Bradenhead flange is changed during a workover, the elevation of the survey point is disturbed; therefore, subsidence or the subsidence rate cannot be determined for the time period between the surveys immediately before and following the workover.

[6] The elevations reported by the surveyors have been adjusted to be with respect to GPS1 with an assumed constant elevation of 5.906 feet.

**Table 3-2. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Page 1 of 2)**
**(Dow)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CLIFTON WELL 1 | 3.716 | 3.666 | 3.636 | 3.544 | 3.507 | 3.463 | 3.284 | 3.365 | 3.313 | 3.315 | 3.190 | 3.082 | 3.014 | 2.974 | 2.949 | 2.949 |
| CLIFTON WELL 6 | 3.620 | 3.587 | 3.593 | 3.477 | 3.415 | 3.361 | 3.286 | 3.262 | 3.166 | 3.133 | 2.969 | 2.793 | 2.689 | 2.639 | 2.612 | 2.584 |
| DOW WELL 4 | 3.452 | 3.421 | 3.356 | 3.311 | 3.251 | 3.205 | 3.157 | —[a] | 3.079 | 3.069 | 2.963 | 2.777 | 2.721 | 2.665 | 2.625 | 2.600 |
| DOW WELL 7 | 5.142 | 5.117 | 5.118 | 5.077 | 5.063 | 5.030 | —[a] | 4.994 | 4.981 | 5.006 | 4.924 | 4.836 | 4.815 | 4.786 | 4.765 | 4.751 |
| DOW WELL 8 | 7.736 | 7.714 | 7.714 | — | 7.673 | 7.662 | 7.650 | —[a] | 7.602 | (b) | 7.551 | 8.774 | 7.475 | 7.452 | 7.428 | 7.428 |
| DOW WELL 9 | 5.936 | 5.900 | 5.842 | 5.771 | 5.699 | 5.683 | 5.623 | 5.594 | 5.518 | 5.507 | 5.373 | 5.251 | 5.207 | 5.168 | 5.144 | 5.127 |
| DOW WELL 9A | 7.692 | 7.654 | 7.590 | 7.517 | 7.439 | 7.431 | 7.372 | 7.348 | 7.268 | 7.251 | 7.124 | 7.010 | 6.953 | 6.907 | 6.873 | 6.871 |
| DOW WELL 10 | 5.804 | 5.770 | 5.748 | 5.668 | 5.614 | 5.590 | 5.550 | 5.518 | 5.463 | 5.483 | 5.361 | 5.245 | 5.196 | 5.161 | 5.136 | 5.126 |
| DOW WELL 11 | 4.048 | 4.004 | 3.956 | 3.854 | 3.810 | 3.786 | 4.055 | 4.015 | 3.619 | 3.608 | 3.482 | 3.353 | 3.295 | 3.261 | 3.230 | 3.216 |
| DOW WELL 12 | 5.033 | 4.995 | 4.940 | 4.865 | 4.806 | 4.787 | 4.731 | 4.692 | 4.635 | 4.630 | 4.487 | 4.373 | 4.311 | 4.275 | 4.248 | 4.238 |
| DOW WELL 13 | 4.959 | 4.929 | 4.875 | 4.810 | 4.750 | 4.721 | 4.663 | 4.628 | 4.549 | 4.645 | 4.412 | 4.276 | 4.224 | 4.181 | 4.152 | 4.151 |
| DOW WELL 14 | 4.045 | 4.003 | 3.960 | 3.883 | 3.826 | 3.816 | 3.754 | 3.720 | 3.631 | 3.632 | 3.495 | 3.374 | 3.317 | 3.278 | 3.252 | 3.248 |
| DOW WELL 15 | 5.199 | 5.148 | 5.118 | 5.046 | 4.988 | 4.961 | 4.915 | 4.892 | 4.822 | 4.845 | 4.728 | 4.620 | 4.576 | 4.541 | 4.517 | 4.509 |
| DOW WELL 16 | 4.539 | 4.498 | 4.471 | 4.405 | 4.344 | 4.316 | 4.277 | 4.253 | 4.183 | 4.204 | 4.079 | 3.984 | 3.945 | 3.911 | 3.893 | 3.893 |
| DOW WELL 17 | 4.380 | 4.325 | 4.297 | 4.239 | 4.177 | 4.144 | 4.115 | 4.100 | 4.045 | 4.046 | 3.949 | 3.853 | 3.826 | 3.785 | 3.760 | 3.757 |
| DOW WELL 18 | 6.303 | 6.262 | 6.219 | 6.117 | 6.057 | 5.995 | —[a] | 5.904 | 5.814 | 5.737 | 5.564 | 5.241 | 5.112 | 5.041 | 4.999 | 4.964 |
| DOW WELL 19 | 6.099 | 6.033 | 6.016 | 5.917 | 5.863 | 5.844 | 5.744 | 5.714 | 5.650 | 5.587 | 5.467 | 5.244 | 5.158 | 5.098 | 5.061 | 5.055 |
| DOW WELL 20 | 6.456 | 6.391 | 6.386 | 6.344 | 6.286 | 6.254 | 6.221 | 6.215 | 6.154 | 6.169 | 6.079 | 6.009 | 5.983 | 5.958 | 5.934 | 5.934 |
| DOW WELL 21 | 6.504 | 6.446 | 6.440 | 6.403 | 6.362 | 6.345 | 6.317 | 6.318 | 6.281 | 6.296 | 6.229 | 6.165 | 6.146 | 6.119 | 6.051 | 6.093 |
| DOW WELL 22 | 6.232 | 6.189 | 6.172 | 6.123 | 6.080 | 6.055 | 6.034 | 5.991 | 5.981 | 6.009 | 5.904 | 5.844 | 5.884 | 5.814 | 5.789 | 5.788 |
| GRACE WELL 1 | 3.421 | 3.371 | 3.344 | 3.292 | 3.262 | 3.230 | 3.209 | —[a] | 3.103 | 3.107 | 3.002 | 2.857 | 2.823 | 2.779 | 2.749 | 2.727 |
| GRACE WELL 3 | 4.393 | 4.401 | 4.348 | 4.353 | 4.317 | 4.250 | 4.226 | 4.206 | 4.175 | 4.200 | 4.117 | 4.017 | 3.997 | 3.969 | 3.941 | 3.941 |
| GRACE WELL 5[c] | 3.800 | 3.807 | 3.744 | 3.739 | 3.695 | 5.725 | 5.698 | 5.673 | 5.639 | 5.634 | 5.544 | 5.413 | 5.384 | 5.352 | 5.317 | 5.308 |
| DOW W.W. 1 | 4.475 | 4.481 | 4.464 | 4.432 | 4.381 | 9.362 | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] |
| DOW W.W. 2 | 4.014 | 3.975 | 3.956 | 3.900 | 3.977 | 3.837 | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] |
| DOW W.W. 3 | 4.033 | 3.995 | 4.009 | 3.977 | 4.050 | 4.050 | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] |
| DOW W.W. 4 | 3.111 | 3.090 | 3.016 | 2.967 | 2.907 | 3.050 | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] |
| DOW W.W. 7 | 9.885 | 9.897 | 9.895 | 9.945 | 9.875 | 9.837 | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] | —[d] |
| DOW MON. 01 | 2.409 | 2.377 | 2.366 | 2.324 | 2.314 | 2.276 | 2.247 | 2.222 | 2.218 | 2.235 | 2.148 | 2.040 | 2.004 | 1.974 | 1.940 | 1.927 |
| DOW MON. 05 | 2.404 | 2.368 | 2.362 | 2.311 | 2.289 | 2.267 | 2.238 | 2.212 | 2.206 | 2.217 | 2.133 | 2.018 | 1.986 | 1.959 | 1.929 | 1.915 |
| DOW MON. 06 | 0.749 | 0.698 | 0.682 | 0.618 | 0.590 | 0.556 | 0.519 | 0.484 | 0.466 | 0.478 | 0.375 | 0.209 | 0.165 | 0.124 | 0.086 | 0.063 |
| DOW MON. 07 | 3.306 | 3.272 | 3.219 | 3.168 | 3.116 | 3.072 | 3.027 | 2.987 | 2.960 | 2.959 | 2.851 | 2.657 | 2.605 | 2.556 | 2.508 | 2.479 |
| DOW MON. 08 | 6.185 | 6.148 | 6.141 | 6.096 | 6.077 | 6.033 | 6.002 | 5.977 | 5.966 | 5.964 | 5.887 | 5.778 | 5.745 | 5.720 | 5.695 | 5.675 |
| DOW MON. 09 | (0.073) | (0.088) | (0.173) | (0.172) | (0.227) | (0.304) | (0.348) | (0.390) | (0.425) | —[f] | (0.545) | —[f] | —[f] | —[f] | (0.865) | (0.881) |
| DOW MON. 10 | 0.270 | 0.226 | 0.161 | 0.096 | 0.043 | (0.010) | (0.061) | (0.100) | (0.148) | —[f] | (0.275) | (0.477) | (0.539) | (0.596) | (0.648) | (0.679) |
| DOW MON. 11 | 1.316 | 1.316 | 1.247 | 1.257 | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] |

**Table 3-2. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Page 2 of 2)**
**(Dow)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DOW MON. 12 | 3.092 | 3.036 | 3.022 | 2.977 | 2.920 | 2.893 | 2.856 | 2.842 | 2.793 | —[g] | —[g] | —[g] | —[g] | —[g] | 2.532 | 2.529 |
| DOW MON. 13 | 2.347 | 2.285 | 2.280 | 2.243 | 2.194 | 2.174 | 2.150 | 2.143 | 2.100 | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] |
| DOW MON. 14 | 1.630 | 1.604 | 1.553 | 1.481 | 1.426 | 1.375 | 1.326 | 1.297 | 1.230 | 1.253 | 1.116 | —[f] | —[f] | —[f] | 0.845 | 0.833 |
| DOW MON. 15 | 1.660 | 1.628 | 1.591 | 1.512 | 1.463 | 1.436 | 1.383 | —[f] | —[f] | 1.296 | 1.152 | —[f] | —[f] | —[f] | 0.919 | 0.917 |
| DOW MON. 16 | 2.437 | 2.413 | 2.355 | 2.246 | 2.202 | 2.155 | 2.094 | 2.064 | 1.977 | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] | —[g] |
| DOW MON. 17 | 1.612 | 1.585 | 1.531 | 1.423 | 1.366 | 1.313 | 1.249 | 1.221 | 1.127 | 1.051 | 0.876 | —[f] | —[f] | —[f] | 0.342 | 0.304 |
| DOW MON. 18 | 2.961 | 2.926 | 2.906 | 2.800 | 2.774 | 2.729 | 2.684 | 2.657 | 2.578 | 2.562 | 2.407 | 2.203 | 2.129 | 2.085 | 2.047 | 2.043 |
| DOW MON. 19 | 2.233 | 2.212 | 2.191 | 2.127 | 2.087 | 2.059 | 2.027 | 2.011 | 1.961 | 1.989 | 1.879 | 1.791 | 1.757 | 1.736 | 1.711 | 1.716 |
| GRACE WELL 3A | — | 3.958 | 3.908 | 3.913 | 3.882 | 3.808 | 3.783 | 3.764 | 3.737 | 3.746 | 3.661 | 3.564 | 3.538 | 3.503 | 3.473 | 3.467 |
| GRAND BAYOU MON. 3 | — | 2.320 | 2.269 | 2.245 | 2.203 | 2.157 | 2.121 | 2.097 | 2.083 | 2.092 | 2.003 | 1.867 | 1.836 | 1.801 | 1.761 | 1.753 |
| GRAND BAYOU MON. 4 | 3.746 | 3.724 | 3.681 | 3.640 | 3.595 | 3.543 | 3.510 | 3.480 | 3.461 | 3.470 | 3.371 | 3.209 | 3.171 | 3.131 | 3.089 | 3.072 |
| GRAND BAYOU MON. 6 | 7.519 | 7.515 | — | 7.474 | 7.443 | 7.393 | 7.372 | 7.361 | 7.361 | 7.389 | 7.305 | 7.205 | 7.194 | 7.170 | 7.143 | 7.141 |
| GRAND BAYOU MON. 8 | — | 3.226 | 3.202 | — | — | 3.067 | 3.032 | 2.999 | 2.983 | 2.993 | 2.893 | 2.719 | 2.673 | 2.628 | 2.587 | 2.563 |
| GRAND BAYOU MON. 12 | — | 7.035 | 7.034 | 7.003 | 6.988 | 6.955 | 6.937 | 6.915 | 6.918 | 6.943 | 6.865 | 6.788 | 6.767 | 6.741 | 6.719 | 6.715 |
| MON. 3 S/W[h] | 2.671 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| MON. 4 S/E | 4.316 | 4.313 | 4.319 | 4.312 | 4.297 | 4.261 | 4.240 | 4.237 | 4.240 | 4.281 | 4.203 | 4.147 | 4.143 | 4.133 | 4.116 | 4.116 |
| MAGNOLIA WELL | — | — | — | — | — | — | — | — | — | 5.335 | 5.254 | 5.215 | 5.192 | 5.182 | 5.160 | 5.163 |

(a) Not surveyed because of ongoing construction.
(b) Well being worked over.
(c) Survey location changed between 1999 and 2000.
(d) Water wells eliminated from subsidence monitoring network.
(e) Horizontal locations provided by Dow.
(f) Under water.
(g) Benchmark lost or destroyed.
(h) Destroyed by levee construction in 1995.

**Table 3-3. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Occidental-Taft)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HOOKER WELL 1 | 3.578 | 3.529 | 3.525 | 3.475 | 3.431 | 3.375 | 3.321 | 3.299 | 3.244 | 3.187 | 3.127 | 2.942 | 2.904 | 2.827 | 2.782 | 2.755 |
| HOOKER WELL 2 | 3.730 | 3.644 | 3.658 | 3.590 | 3.547 | 3.499 | 3.453 | 3.423 | 3.373 | 3.327 | 3.216 | 2.978 | 2.926 | 2.848 | 2.791 | 2.768 |
| HOOKER WELL 3 | 3.535 | 3.458 | 3.474 | 3.395 | 3.374 | 3.303 | 3.252 | 3.218 | 3.161 | 3.114 | 2.999 | 2.740 | 2.676 | 2.583 | 2.522 | 2.513 |
| HOOKER WELL 4 | 6.496 | 6.443 | 6.436 | 6.368 | 6.330 | 6.270 | 6.216 | 6.192 | 6.134 | 6.109 | 5.997 | 5.783 | 5.733 | 5.651 | 5.613 | 5.592 |
| HOOKER WELL 5 | 6.731 | 6.656 | 6.652 | 6.576 | 6.534 | 6.461 | 6.408 | 6.371 | 6.309 | 6.324 | 6.132 | 5.824 | 5.747 | 5.654 | 5.591 | 5.567 |
| OXY WELL 9[a] | — | — | — | 7.483 | 7.464 | 7.459 | 7.354 | 7.350 | 7.386 | 7.338 | 7.268 | 7.142 | 7.119 | 7.055 | 6.998 | 6.972 |
| OXY WELL 10 | 9.843 | 9.735 | 9.718 | 9.669 | 9.687 | 9.679 | 9.579 | 9.617 | 9.604 | 9.581 | 9.496 | 9.370 | 9.345 | 9.281 | 9.228 | 9.211 |
| OXY W.W. 1A | 3.081 | 3.012 | 3.015 | 2.952 | 2.913 | 2.698 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| OXY W.W. 2[c] | 3.085 | 3.019 | — | — | — | — | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| OXY W.W. 3A | 4.828 | 4.759 | 4.684[d] | 4.610 | 4.582 | 3.789 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| OXY MON. 01 | 1.702 | 1.646 | 1.645 | 1.585 | 1.539 | 1.498 | 1.447 | 1.423 | 1.380 | 1.359 | 1.271 | 1.101 | 1.060 | 0.988 | 0.937 | 0.911 |
| OXY MON. 02 | (0.157) | (0.229) | (0.209) | (0.285) | (0.299) | (0.357) | (0.408) | (0.429) | (0.484) | (0.520) | (0.620) | (0.844) | (0.896) | (0.975) | (1.034) | (1.044) |
| OXY MON. 03 | 3.476 | 3.370 | 3.375 | 3.298 | 3.287 | 3.281 | 3.168 | 3.195 | 3.195 | 3.146 | 3.065 | 2.911 | 2.882 | 2.817 | 2.756 | 2.749 |
| OXY MON. 04 | 2.751 | 2.684 | 2.689 | 2.641 | 2.631 | 2.616 | 2.522 | 2.558 | 2.640 | 2.533 | 2.464 | 2.362 | 2.351 | 2.301 | 2.229 | 2.237 |
| OXY MON. 05 | 2.771 | 2.730 | 2.737 | 2.689 | 2.683 | 2.668 | 2.584 | 2.625 | 2.570 | 2.613 | 2.547 | 2.468 | 2.463 | 2.418 | 2.377 | 2.407 |

(a) This well was added during 1997.
(b) Water wells eliminated from subsidence monitoring network.
(c) This well was removed during 1996.
(d) Well was dismantled; a new mark was set on concrete slab.

**Table 3-4. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Occidental-Geismer (Vulcan))**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HOOKER WELL 6 | 10.424 | 10.363 | 10.367 | 10.317 | 10.286 | 10.279 | 10.184 | 10.210 | 10.221 | 10.185 | 10.103 | 9.983 | 9.964 | 9.910 | 9.852 | 9.765 |
| HOOKER WELL 7[a] | 8.727 | 8.643 | 8.667 | 8.609 | 8.576 | 10.088 | 9.983 | 10.031 | 10.026 | 9.980 | 9.913 | 9.782 | 9.751 | 9.694 | 9.635 | 9.592 |
| HOOKER WELL 8 | 8.756 | 8.659 | 8.683 | 8.607 | 8.601 | 8.618 | 8.525 | 8.560 | 8.575 | 8.538 | 8.462 | 8.369 | 8.348 | 8.312 | (b) | 5.435 |

(a) Survey location changed between 1999 and 2000.
(b) Plugged and abandoned.

**Table 3-5. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Crosstex (El Paso))[a]**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EL PASO RAWMAKE WELL 1 | 4.034 | 3.996 | 3.982 | 3.933 | 3.889 | 3.891 | 3.770 | 3.823 | 3.834 | 3.771 | 3.714 | 3.556 | 3.527 | 3.470 | 3.410 | 3.386 |
| EL PASO PROPANE WELL 2 | 3.750 | 3.683 | 3.657 | 3.595 | 3.546 | 3.552 | 3.404 | 3.459 | 3.464 | 3.394 | 3.352 | 3.130 | 3.099 | 3.033 | 2.970 | 2.914 |
| EL PASO MON. 01 | 2.582 | 2.540 | 2.529 | 2.486 | 2.447 | 2.441 | 2.322 | 2.391 | 2.403 | 2.364 | 2.328 | 2.189 | 2.179 | 2.129 | 2.078 | 2.067 |
| EL PASO MON. 02 | 2.439 | 2.392 | 2.380 | 2.337 | 2.273 | 2.297 | 2.169 | 2.236 | 2.244 | 2.198 | 2.161 | 2.013 | 1.995 | 1.948 | 1.892 | 1.869 |
| EL PASO MON. 03 | 2.046 | 1.971 | 1.949 | 1.889 | 1.843 | 1.835 | 1.702 | 1.761 | 1.769 | 1.697 | 1.653 | 1.449 | 1.416 | 1.351 | 1.292 | 1.263 |
| EL PASO MON. 04 | 3.541 | 3.492 | 3.499 | 3.446 | 3.443 | 3.425 | 3.335 | 3.385 | 3.399 | 3.372 | 3.305 | 3.226 | 3.221 | 3.175 | 3.133 | 3.164 |
| EL PASO MON. 05 | 3.151 | 3.111 | 3.126 | 3.092 | 3.053 | 3.049 | 2.936 | —[b] | —[c] | —[c] | —[c] | —[c] | —[c] | —[c] | —[c] | —[c] |

(a) El Paso wells and benchmarks identified with the letters “EN” in Figure 4-1.
(b) Benchmark disturbed.
(c) Benchmark destroyed between 2002 and 2003 surveys.

**Table 3-6. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet) (Bridgeline)[a]**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BRIDGELINE GAS WELL 1[b] | — | 6.194 | 6.172 | 6.114 | 6.073 | 6.079 | 5.938 | 6.012 | 6.030 | 5.964 | 5.907 | 5.727 | 5.703 | 5.633 | 5.585 | 5.548 |
| BRIDGELINE MON. 01 | | | | | | | | 3.171 | 3.176 | 3.103 | 3.058 | 2.854 | 2.810 | 2.742 | 2.680 | 2.631 |
| BRIDGELINE MON. 02 | | | | | | | | 2.857 | 2.866 | 2.795 | 2.748 | 2.545 | 2.510 | 2.443 | 2.386 | 2.360 |
| BRIDGELINE MON. 03 | | | | | | | | 3.435 | 3.443 | 3.363 | 3.327 | 3.112 | 3.078 | 3.016 | 2.959 | 2.940 |
| BRIDGELINE MON. 04 | | | | | | | | 4.772 | 4.778 | 4.707 | 4.658 | (c) | (c) | 4.320 | 4.272 | 4.256 |

(a) Bridgeline wells and benchmarks identified with the letters “EN” in Figure 4-1.
(b) Well added during 1996.
(c) Under water.

**Table 3-7. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet)**
**(Georgia Gulf)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GEORGIA GULF WELL 1 | 6.892 | 6.855 | 6.858 | 6.781 | 6.735 | 6.701 | 6.647 | 6.622 | 6.570 | 6.548 | 6.448 | 6.292 | 6.264 | 6.198 | 6.162 | 6.155 |
| GEORGIA GULF WELL 2 | 6.226 | 6.174 | 6.191 | 6.123 | 6.096 | 6.048 | 6.004 | 5.990 | 5.925 | 5.907 | 5.802 | 5.680 | 5.652 | 5.596 | 5.557 | 5.557 |
| GEORGIA GULF WELL 3 | 6.322 | 6.281 | 6.312 | 6.233 | 6.221 | 6.164 | 6.135 | 6.115 | 6.053 | 6.046 | 5.955 | 5.864 | 5.836 | 5.790 | 5.757 | 5.764 |
| GEORGIA GULF WELL 4 | 7.611 | 7.551 | 7.562 | 7.510 | 7.462 | 7.425 | 7.366 | 7.346 | 7.283 | 7.241 | 7.156 | 7.003 | 6.978 | 6.909 | 6.871 | 6.860 |
| GGBM MON. 01 | 2.479 | 2.428 | 2.426 | 2.370 | 2.323 | 2.294 | 2.245 | 2.231 | 2.192 | 2.180 | 2.099 | 1.965 | 1.944 | 1.886 | 1.843 | 1.834 |
| GGBM MON. 02 | 3.076 | 3.030 | 3.037 | 2.995 | 2.957 | 2.939 | 2.899 | 2.895 | 2.864 | 2.875 | 2.804 | 2.721 | 2.714 | 2.664 | 2.633 | 2.637 |
| GGBM MON. 03 | 1.250 | 1.212 | 1.220 | 1.165 | 1.119 | 1.090 | 1.049 | 1.038 | 0.996 | 0.994 | 0.910 | 0.788 | 0.771 | 0.714 | 0.654 | 0.651 |
| GEORGIA GULF W.W. 1A | — | 8.221 | 8.231 | 8.162 | 8.114 | 8.079 | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] |
| GEORGIA GULF W.W. 2A | — | 6.395 | 6.479[b] | 6.405 | 6.382 | 6.409 | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] | —[a] |

(a) Water wells eliminated from subsidence monitoring network.
(b) Could not find existing survey mark. A new mark was made.

**Table 3-8. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet)**
**(Union Carbide)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UCAR WELL 1 | 4.803 | 4.805 | 4.735 | 4.774 | 4.712 | 4.667 | 4.649 | 4.622 | 4.599 | 4.598 | 4.527 | 4.465 | 4.437 | 4.413 | 4.389 | 4.388 |
| UCAR WELL 2 | 5.837 | 5.845 | 5.789 | 5.825 | 5.775 | 5.735 | 5.703 | 5.671 | 5.657 | 5.686 | 5.591 | 5.511 | 5.503 | 5.471 | 5.452 | 5.454 |
| UCAR MON. 01 | 2.294 | 2.309 | 2.265 | 2.311 | 2.259 | 2.199 | 2.194 | 2.177 | 2.175 | 2.202 | 2.130 | 2.056 | 2.043 | 2.029 | 2.014 | 2.021 |
| UCAR MON. 02 | 3.177 | 3.188 | 3.157 | 3.205 | 3.157 | 3.102 | 3.100 | 3.087 | 3.092 | 3.131 | 3.068 | 3.011 | 3.006 | 2.994 | 2.984 | 2.993 |
| UCAR SWD 1 | 3.447 | 3.460 | 3.426 | 3.460 | 3.410 | 3.391 | 3.417 | 3.374 | 3.368 | 3.418 | 3.338 | 3.289 | 3.277 | 3.271 | 3.268 | 3.285 |

**Table 3-9. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet)**
**(Acadian (Enterprise (Shell)))**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHELL WELL 1[a] | 3.129[a] | 3.119 | 3.071 | 3.001 | 2.959 | 4.604 | 4.571 | 4.559 | 4.498 | 4.508 | 4.402 | 4.296 | 4.264 | 4.231 | 4.195 | 4.188 |

(a) During the 1995 survey, the benchmark was under water and the measurement was taken from a point 0.56 foot below the Bradenhead flange. The elevation was corrected by the surveyor to a point on the lower Bradenhead flange during the 1996 survey. The survey location was modified in 2000.

**Table 3-10. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet)**
**(Promix LLC)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PROMIX WELL 1 | 5.674 | 5.620 | 5.606 | 5.523 | 5.520 | 5.476 | 5.447 | 5.423 | 5.404 | 5.439 | 5.307 | 5.157 | 5.119 | 5.081 | 5.055 | 5.032 |
| PROMIX WELL 2 | 4.805 | 4.752 | 4.759 | 4.686 | 4.672 | 4.641 | 4.611 | 4.585 | 4.617 | 4.627 | 4.501 | 4.386 | 4.338 | 4.309 | 4.282 | 4.263 |
| PROMIX WELL 3[a] | 5.360 | 5.295 | 5.309 | 5.261 | 4.283 | 4.269 | 4.246 | 4.225 | 4.207 | 4.237 | 4.146 | 4.034 | 4.006 | 3.979 | 3.955 | 3.937 |
| PROMIX WELL 4[b] | 6.638 | 5.592 | 5.624 | 5.556 | 5.560 | 5.543 | 5.529 | 5.511 | 5.498 | 5.554 | 5.438 | 5.350 | 5.337 | 5.308 | 5.288 | 5.285 |
| PROMIX WELL 5[c] | 5.739 | 5.704 | 5.350 | 5.272 | 5.274 | 5.264 | 5.263 | 5.251 | 5.245 | 5.315 | 5.170 | 5.085 | 5.056 | 5.032 | 5.014 | 4.995 |
| PROMIX WELL 6[b] | 7.595 | 5.613 | 5.622 | 5.566 | 5.550 | 5.536 | 5.517 | 5.503 | 5.483 | 5.554 | 5.410 | 5.312 | 5.291 | 5.271 | 5.252 | 5.247 |
| PROMIX W.W. 1 | 6.921 | 6.928 | 6.933 | 6.883 | — | 6.843 | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] |
| PROMIX W.W. 2 | 5.050 | 5.040 | 5.054 | 5.025 | 5.011 | 5.007 | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] | —[e] |
| PROMIX 2A[f] | 7.500 | 7.494 | 7.517 | 7.480 | 7.466 | 6.958 | 6.940 | —[g] | —[h] | —[h] | —[h] | —[h] | —[h] | —[h] | —[h] | —[h] |
| DOW MON. 02 | 4.546 | 4.559 | 4.566 | 4.526 | 4.528 | 4.509 | 4.496 | 4.484 | 4.495 | 4.531 | 4.466 | 4.430 | 4.420 | 4.411 | 4.404 | 4.401 |
| DOW MON. 03 | 2.525 | 2.522 | 2.488 | 2.487 | 2.497 | 2.482 | 2.473 | 2.462 | 2.471 | 2.454 | 2.447 | 2.420 | 2.417 | 2.413 | 2.408 | 2.405 |
| DOW MON. 04 | 4.859 | 4.840 | 4.855 | 4.839 | 4.825 | 4.810 | 4.795 | 4.780 | 4.791 | 4.822 | 4.761 | 4.724 | 4.715 | 4.708 | 4.696 | 4.690 |

(a) Survey location changed between 1998 and 1990.
(b) Survey location changed between 1995 and 1996.
(c) Survey location changed between 1996 and 1997.
(d) Horizontal locations provided by Dow.
(e) Water wells eliminated from subsidence monitoring network.
(f) Survey location changed between 1999 and 2000.
(g) Not surveyed due to ongoing construction.
(h) Well plugged and abandoned.

**Table 3-11. Reported Locations and Level Survey Elevations (ft) Relative to Elevation of GPS1 (Assumed as 5.906 Feet)**
**(GPS and Reference Benchmark)**

| Benchmark | 1995 Survey | 1996 Survey | 1997 Survey | 1998 Survey | 1999 Survey | 2000 Survey | 2001 Survey | 2002 Survey | 2003 Survey | 2004 Survey | 2005 Survey | 2008 Survey | 2009 Survey | 2010 Survey | 2011 Survey | 2012 Survey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GPS1 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 | 5.906 |
| GPS2 | 3.967 | 3.944 | 3.891 | 3.787 | 3.749 | 3.725 | 3.685 | 3.628 | 3.539 | 3.549 | 3.388 | 3.194 | 3.121 | 3.086 | 3.052 | 30.25 |
| GPS3 | 3.501 | 3.472 | 3.473 | 3.433 | 3.423 | 3.417 | 3.369 | 3.391 | 3.413 | 3.388 | 3.324 | 3.262 | 3.263 | 3.228 | 3.192 | 3.200 |
| GPS4[a] | — | — | 3.176 | 3.099 | 3.106 | 3.085 | 3.056 | 3.013 | 3.011 | 2.967 | 2.884 | 2.732 | 2.704 | 2.641 | 2.580 | 2.591 |
| Dow Mon. 20[b] | | | | | | | | 6.724 | 6.727 | 6.727 | 6.727 | 6.719 | 6.732 | 6.733 | 6.736 | 6.738 |

(a) Added in 1996.
(b) Added in 2002.

# 4.0 SUBSIDENCE ANALYSIS

Subsidence at Napoleonville is not measured directly. Rather, precision level surveys are performed on a regular basis, during which time, the differences in elevation between the GPS1 benchmark and the level survey benchmarks are determined. Assuming the elevation of the GPS1 benchmark is known and constant, the elevations of all of the level survey or subsidence monitoring benchmarks are calculated. These calculated elevations are then used to calculate the annual change in elevation (the subsidence rate) for all benchmarks.

## 4.1 TECHNICAL APPROACH

The objective of this report is to determine the ground subsidence that is occurring at the Napoleonville site and compare it to subsidence at other domes and predicted subsidence at the Napoleonville salt dome [Nieland, 1998]. The technical approach used to evaluate the measured subsidence is to assume that GPS Benchmark GPS1, an "off-dome" benchmark, is not moving vertically. All benchmark subsidence rates are based on this assumption.

## 4.2 MEASURED SUBSIDENCE RATES

Because the yearly subsidence that occurs at some locations at the Napoleonville site is not significantly greater than the survey measurement error, comparisons of surveys 1 year apart are not always meaningful. Thus most of the subsidence rates reported in this report are based on more than two annual surveys. The subsidence rates (inches/year) for the period January 1995 through August 2012 for the Napoleonville subsidence network are provided in Figure 4-1. The rates illustrated in this figure are the subsidence rates that were calculated using a least-squares fit through the calculated elevations of each of the benchmarks for all 16 surveys. Calculated subsidence rates for new benchmarks or wellheads are not included in the development of Figure 4-1 until the benchmark or well has been surveyed at least three times. The plot in Figure 4-1 in this report was developed with the restriction that no contours are constructed for areas more than 1,000 feet from a benchmark or wellhead.

The largest calculated linear subsidence rate over this 17-year time period (slightly less than 1 inch per year) occurs near the center of the salt dome at Dow Well No. 18. The lowest subsidence rates occur in the southeast and east portions of the dome.

Figure 4-2 illustrates the subsidence rates over the time period of 2005 to 2012. The maximum subsidence rate illustrated in this figure is slightly more than 1 inch per year near Dow Well No. 18.

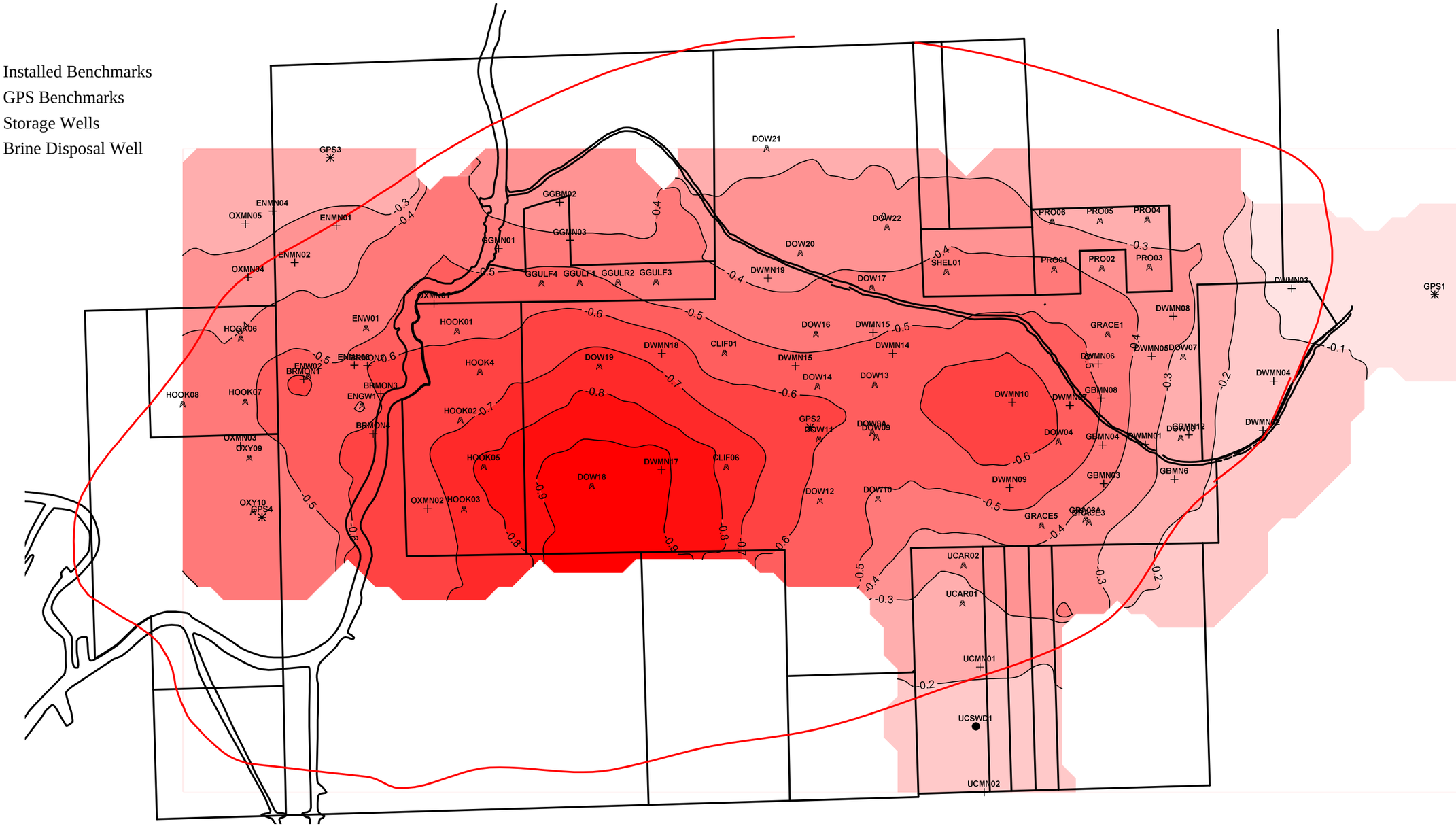


**Figure 4-1.** Measured Subsidence Rates (Inches/Year) for 1995 Through 2012.

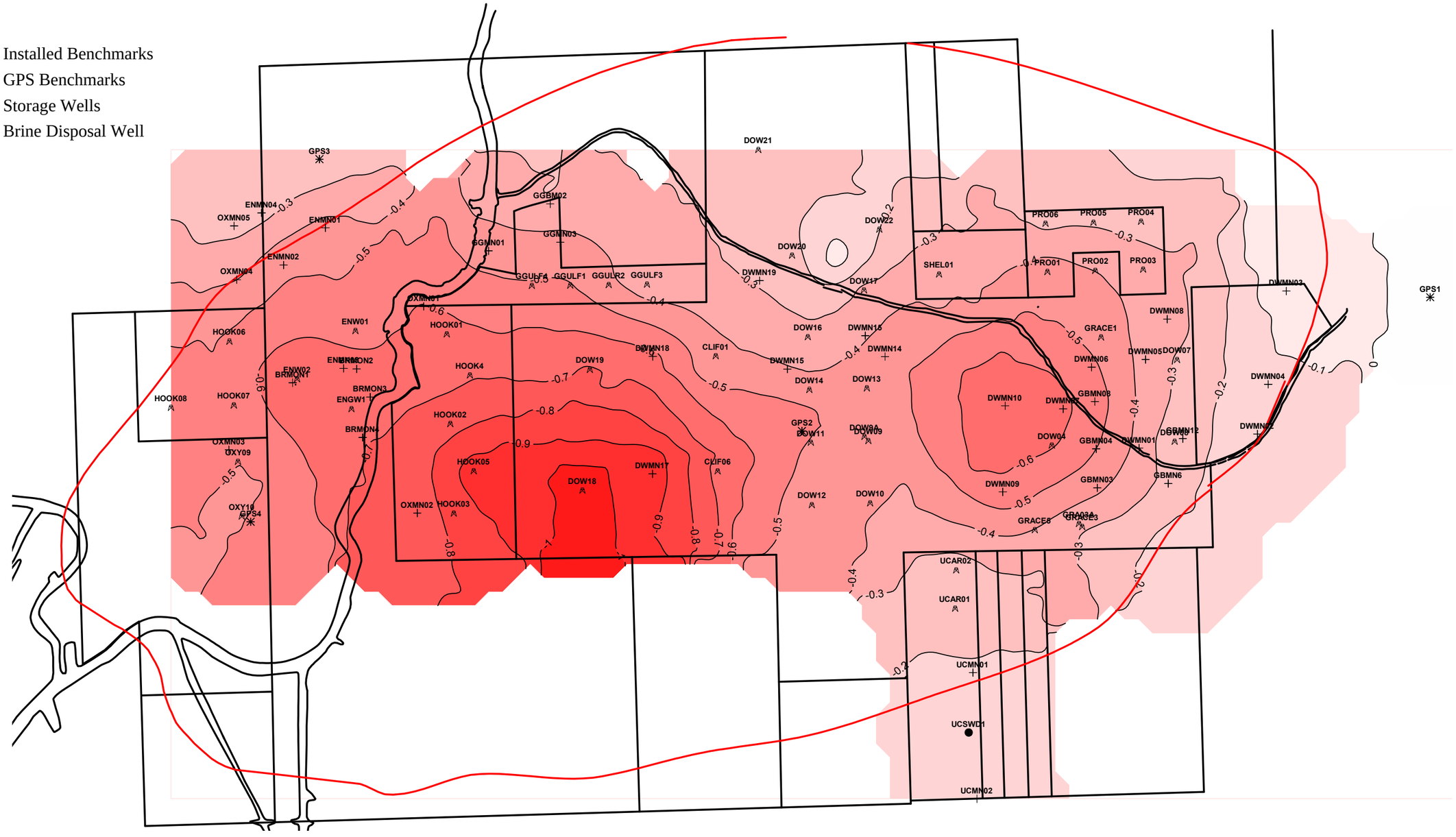


**Figure 4-2.** Measured Subsidence Rates (Inches/Year) for 2005 Through 2012.

Figure 4-3 illustrates the subsidence rates over the time period from 2009 through 2012 (three subsidence surveys). This figure illustrates a significant change in subsidence rate over Dow Well No. 18. The subsidence rate at Dow Well No. 18 over the time period of 2009 to 2012 is about 40 percent less than the rate of the time period of 2005 to 2012. The maximum subsidence rate over the time period of 2009 to 2012 is over the OXY Geismer Well No. 1 (labeled "HOOK06" in Figure 4-3). Figure 4-4 illustrates the subsidence rates over the time period from the 2011 survey to the 2012 survey. The shading (red) levels used in the previous subsidence rate contours are identical in this figure. The maximum subsidence rate in this figure (approximately 1.1 inches per year) is exhibited at the OXY Geismer Well No. 1. It should be kept in mind that this figure was developed with data from only two surveys.

## 4.3 TOTAL SUBSIDENCE

Figure 4-5 illustrates the total vertical subsidence that has occurred since the precision level surveys were initiated in 1995. The maximum subsidence over the 17-year monitoring time frame has been slightly more than 16 inches near Dow Well No. 18.

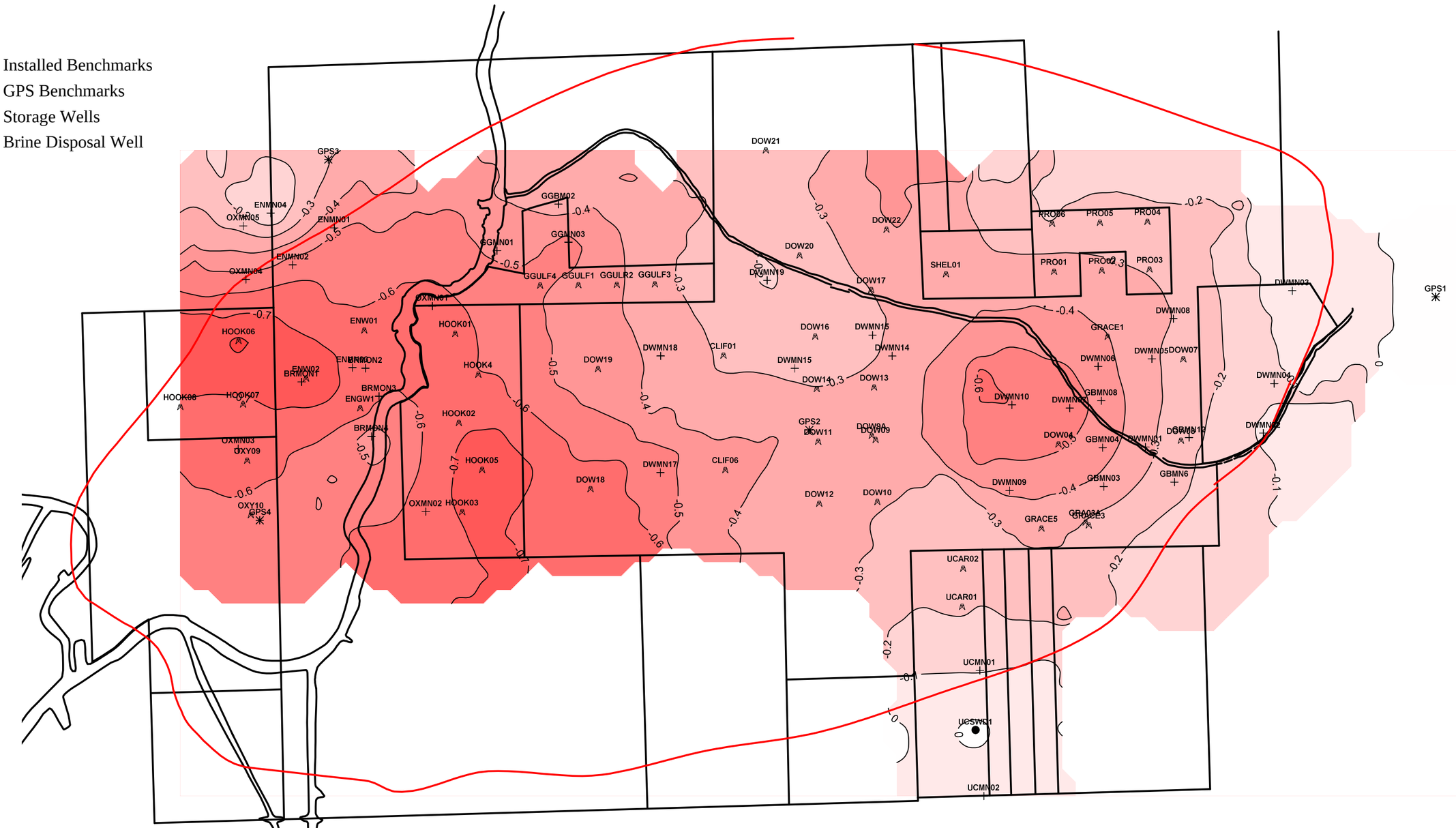


**Figure 4-3.** Measured Subsidence Rates (Inches/Year) for 2009 Through 2012.

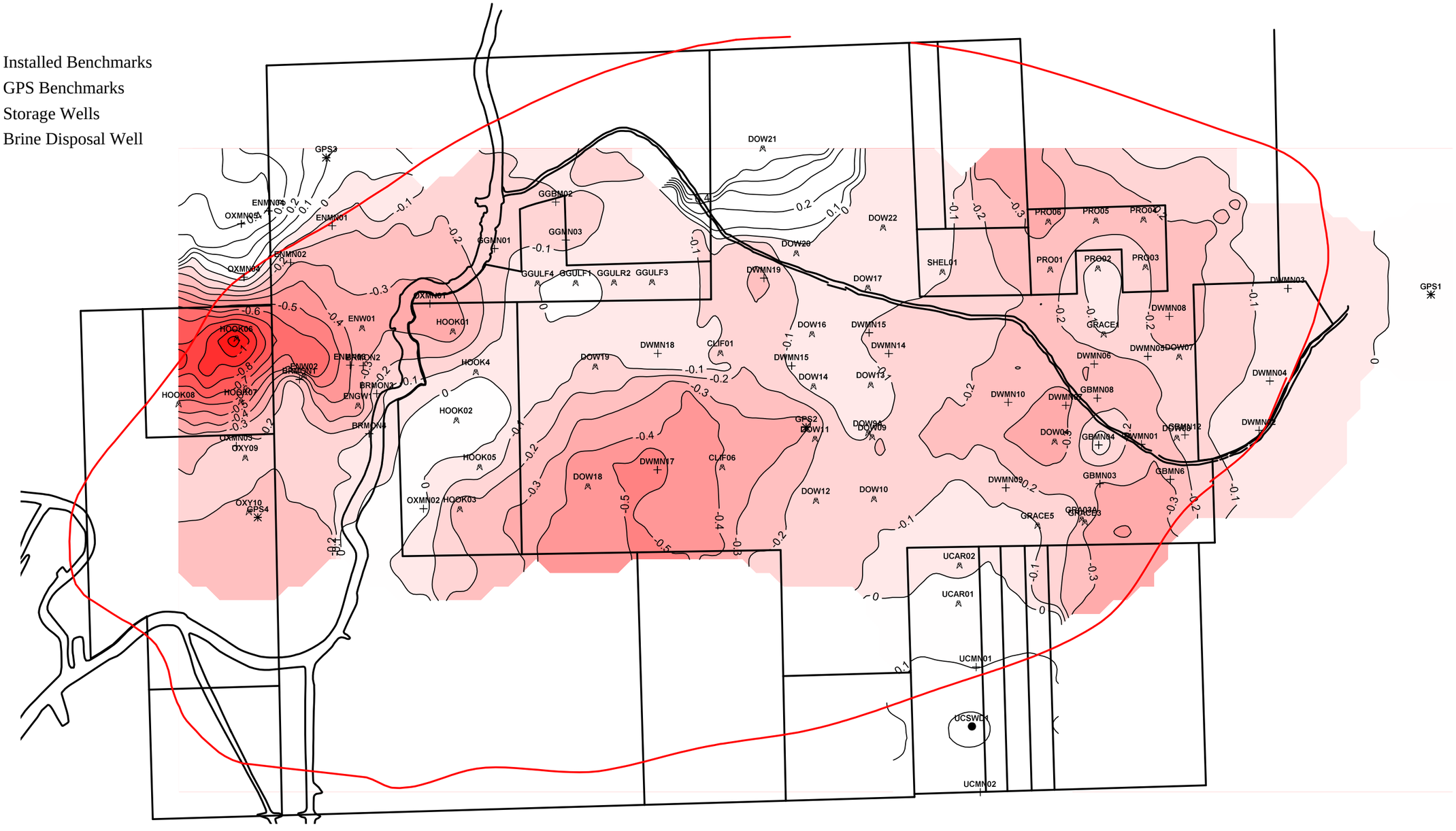


**Figure 4-4.** Measured Subsidence Rates (Inches/Year) From 2011 to 2012.

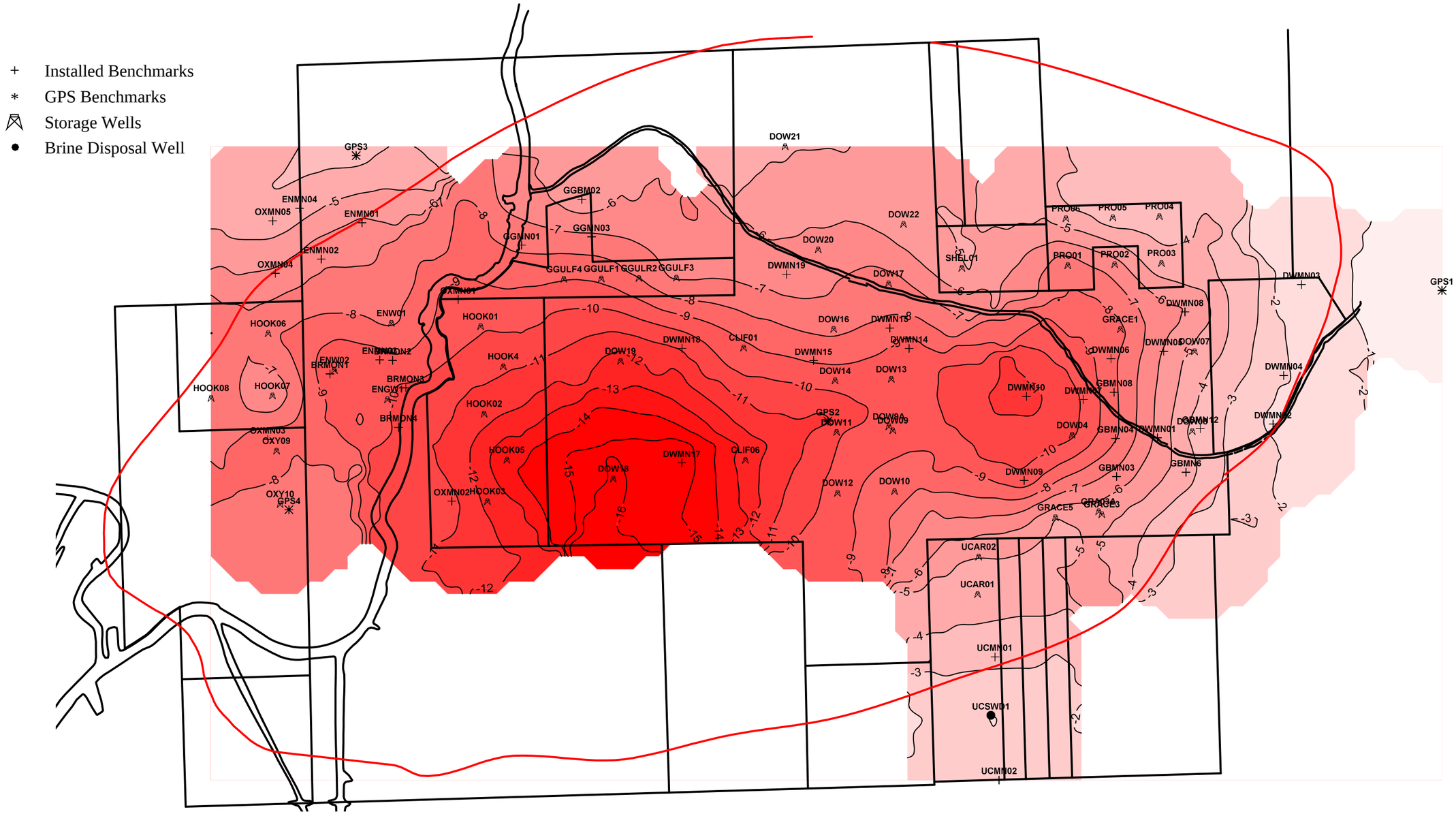


**Figure 4-5.** Total Subsidence (Inches) Over the Time Period of 1995 Through 2012 at the Napoleonville Salt Dome.

# 5.0 MAXIMUM HORIZONTAL STRAINS

Vertical ground subsidence can induce loads on pipelines and other structures on the surface. If the ground at point "A" subsides (vertically) at a greater rate than the ground at point "B", then the horizontal distance from point "A" to point "B" increases, which results in an extensional or tensile strain. Sometimes, this extensional horizontal strain produces surface cracks in the ground surface.

The horizontal strains described above can produce loadings on pipelines. In an effort to evaluate the significance of subsidence-induced horizontal strains at the Napoleonville salt dome, the maximum horizontal strain associated with the vertical ground subsidence was approximated using the expression:

$$\text{Maximum horizontal strain} = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \qquad (5\text{-}1)$$

where:

$z$ = the vertical ground subsidence rate from measured vertical elevation changes

$x$, $y$ = horizontal surface coordinates.

Applying the mathematical operator above, the 2005–2012 vertical ground subsidence rates were assessed to determine the maximum horizontal strain rate over the dome. A contour plot of the estimated maximum horizontal strain rates is illustrated in Figure 5-1. The contours in this figure are based on the vertical subsidence measured over the time period of 2005 through 2012. Most of the storage field exhibits horizontal strain rates generally less than about $2(10^{-5})$/year. Assuming a pipeline with a Young's modulus of about $30(10^6)$/year, these horizontal strains would translate to subsidence-induced tensile stresses in the piping of less than about 600 psi/year. As illustrated in Figure 5-1, there are areas experiencing subsidence-induced horizontal strains slightly in excess of about $4(10^{-5})$/year. These areas generally surround the regions of highest vertical subsidence. The horizontal strain rates have been estimated based on a limited database of measurements and this should be kept in mind when developing conclusions.

Figure 5-2 illustrates maximum horizontal strain rate magnitudes for the time period of 2009 to 2012. The maximum horizontal strain rates have noticeably decreased in the vicinity of Dow Well No. 18.

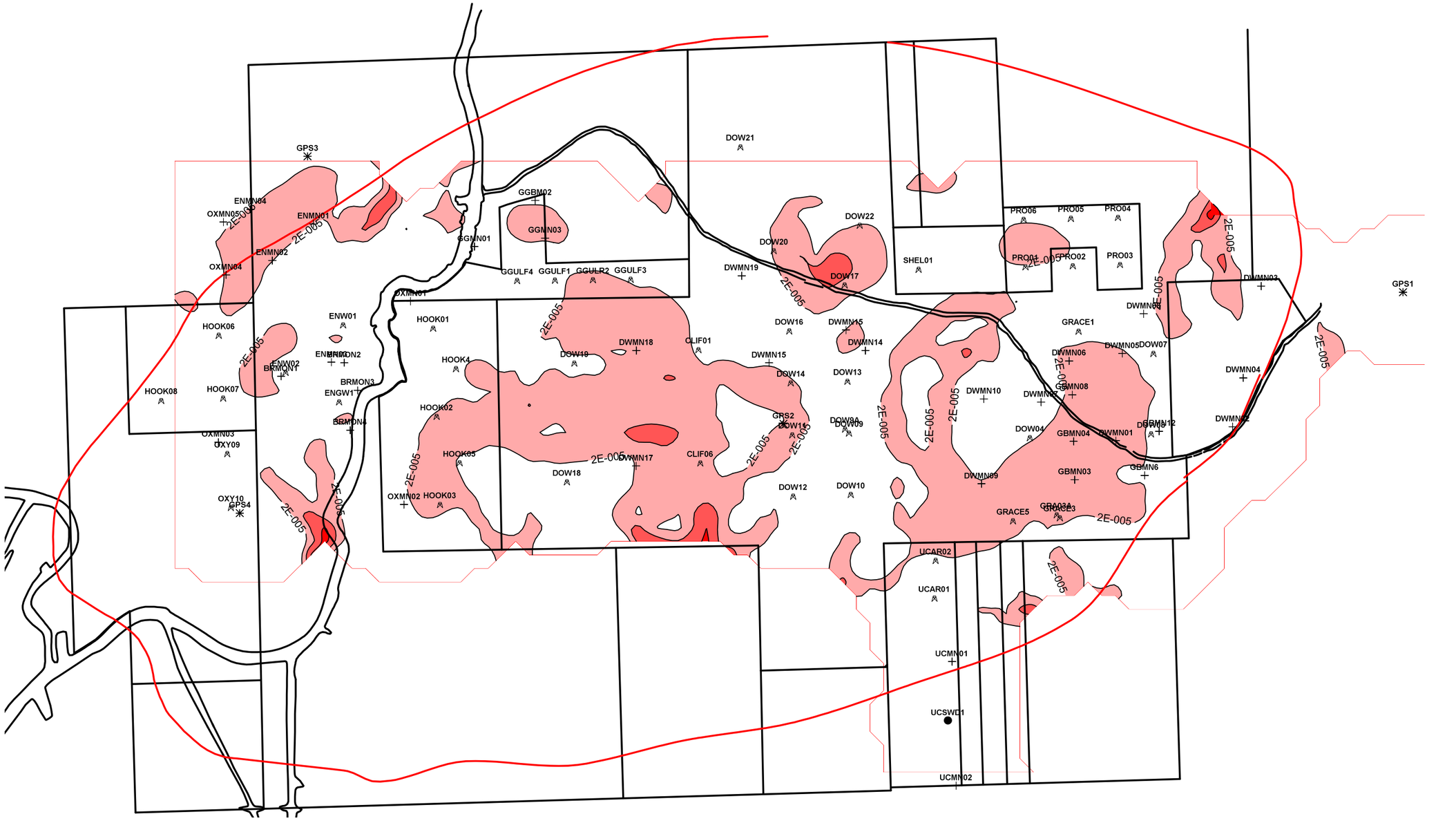


**Figure 5-1.** Estimated Maximum Horizontal Strain Rated at the Napoleonville Salt Dome Based on the Vertical Subsidence Measured Over the Time Period of 2005 Through 2012.


**Figure 5-2.** Estimated Maximum Horizontal Strain Rated at the Napoleonville Salt Dome Based on the Vertical Subsidence Measured Over the Time Period of 2009 Through 2012.

# 6.0 SUMMARY

Sixteen precision level surveys of the Napoleonville benchmark network have been completed for the purpose of evaluating subsidence rates. The largest measured subsidence rate over the period from 1995 to 2012 (about 0.96 inch per year) occurs near the center of the dome, near Dow Well No. 18. The subsidence rate near Dow Well No. 18 is about 1.2 inches per year over the time period of 2005 to 2010. Subsidence rates on the perimeter of the dome are less than about 0.25 inch per year.

Subsidence rates over the last several years have been reduced by about 40 percent in the vicinity of Dow Well No. 18. The maximum subsidence in recent years appears at OXY Geismer Well No. 1. Horizontal strain rates are estimated to be reasonably low, particularly over the last several years.

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