A GIS-BASED APPROACH TO CHARACTERIZING VERMONT'S GROUNDWATER RESOURCES

Marjorie Gale (1), George Springston (2), John Van Hoesen (3) and Laurence Becker (1)
(1) Vermont Geological Survey, Montpelier, VT; (2) Norwich University, Northfield, VT; (3) Green Mountain College, Poultney, VT

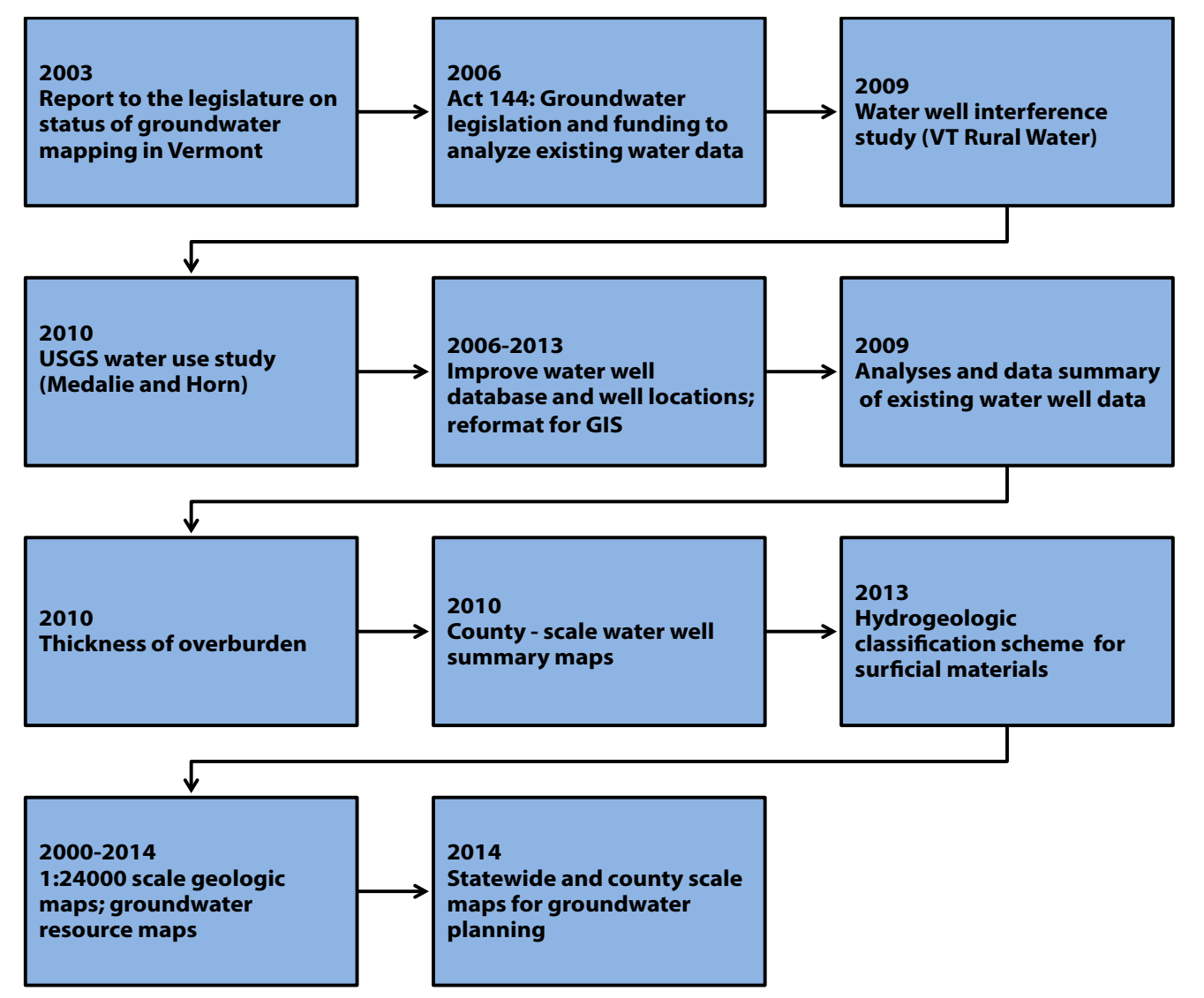
ABSTRACT

The Vermont Geological Survey (VGS) is developing a framework for characterization of groundwater resources (GWR) by integrating bedrock and surficial maps with existing water well data. In 2008, the VGS began assessing GWR using: 1) the Centennial Geologic Map of Vermont (1:250000 scale), 2) digital compilation of 1:62500 scale surficial maps, 3) water well database, and 4) available data such as DEM, soils, and potential pollution sources. Completed maps based on these data include: Thickness of Overburden in Vermont (Springston et al, 2012), Statewide Analyses of Bedrock Water Well Data (Gale et al, 2009) and 14 county maps. Other data include a groundwater use study (Medalie and Horn, 2010) and a well interference study (VT Rural Water, 2009).

The Dept. of Environmental Conservation water well database contains >100,000 records with 76 fields such as use code, reported yield and depth, date completed, well type, location, and the type and thickness of materials. A hydrogeological classification code was developed based on porosity and thickness of surficial materials and assigned to each well. The resulting maps:
1) provide favorability assessments for surficial aquifers,
2) allow for spatial analyses within a geographic information system (GIS), and
3) facilitate integration of geochemical and structural data with geologic materials, water quality data and water use data to produce maps which focus our efforts for more detailed projects.

GWR maps also show areas of thin overburden where bedrock wells are needed, areas of thick overburden and favorable materials for higher yield surficial wells, generalized areas of lower yield, relationships to designated town growth areas, and areas of thick impermeable overburden which impede recharge and may promote surface run-off. Although detailed geologic studies are preferred for site work, GIS analyses allow the VGS to generate statewide and county scale maps within a reasonable time frame that can be used to understand and address GWR identification and protection.

FIGURE 1. Chronology of Groundwater Mapping and Regional Planning Maps



2003
Report to the legislature on status of groundwater mapping in Vermont

2006
Act 144: Groundwater legislation and funding to analyze existing water data

2009
Water well interference study (VT Rural Water)

2010
USGS water use study (Medalie and Horn)

2006-2013
Improve water well database and well locations; reformat for GIS

2009
Analyses and data summary of existing water well data

2010
Thickness of overburden

2010
County - scale water well summary maps

2013
Hydrogeologic classification scheme for surficial materials

2000-2014
1:24000 scale geologic maps; groundwater resource maps

2014
Statewide and county scale maps for groundwater planning

FIGURE 10. INFLUENCE OF SURFICIAL MATERIALS

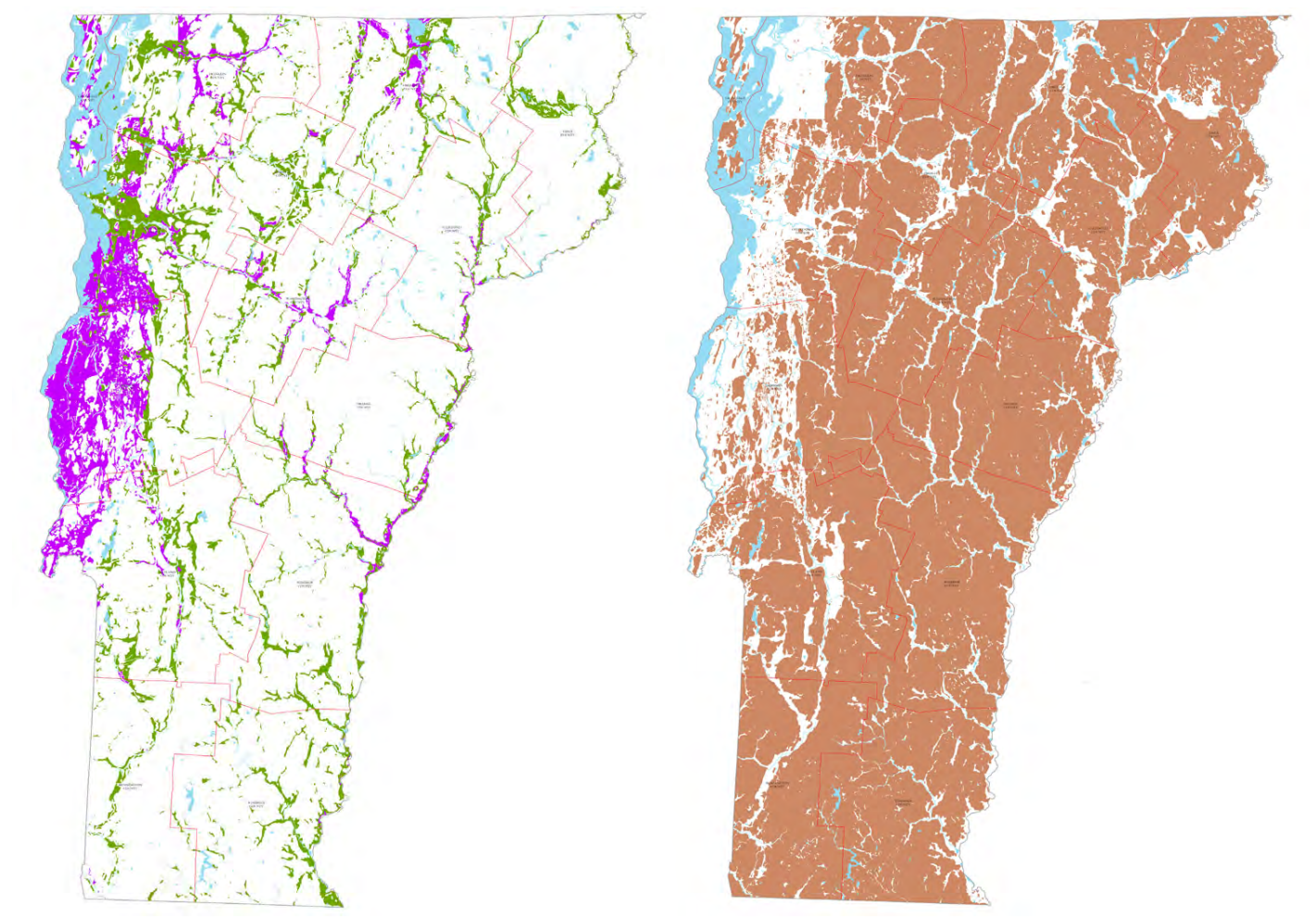


Figure 10a. Clay, silt (purple) and sand and gravel deposits (green).

Figure 10b. Till and exposed bedrock.

FIGURES 10a (left) and 10b (right). Figure 10a shows clay and silt (purple) and sand and gravel (green) as shown on the Surficial Geologic Map of Vermont (1970). The silt and clay may inhibit infiltration of surface water into underlying surficial materials or bedrock or may overlie buried aquifers. Sand and gravel, the porous and permeable materials, allow for direct infiltration of surface waters and may also host shallow aquifers. Figure 10b shows that most of Vermont is till or exposed bedrock, areas where bedrock wells are likely. These areas may also have direct infiltration of water into bedrock fractures and serve as recharge areas to valley aquifers.

FIGURES 2-5. WATER WELL DATA, BEDROCK TYPE, AND IDW ANALYSES

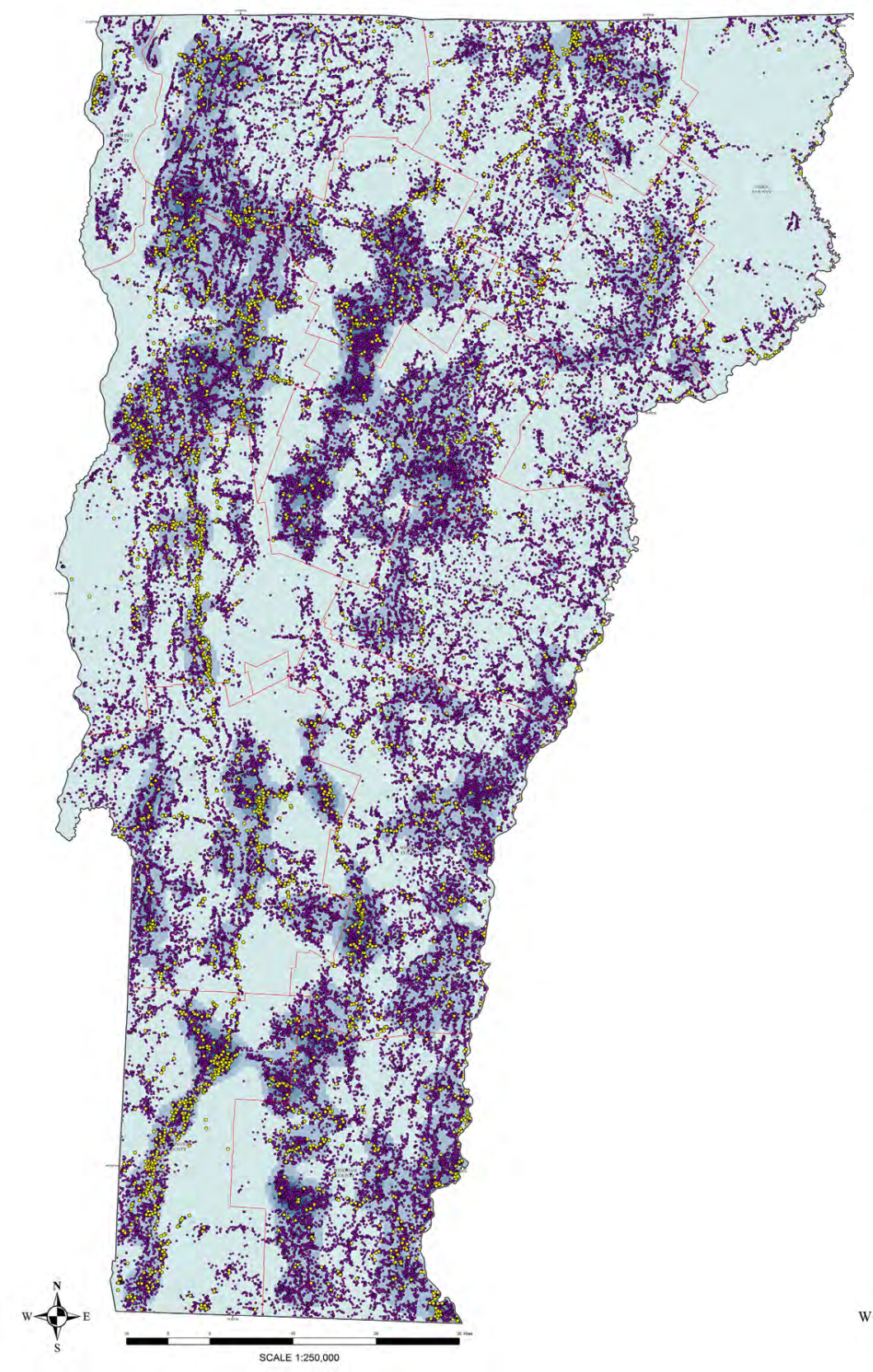


FIGURE 2. Distribution of 93,788 water wells completed in 1966-2006. Database has 76 fields including use, yield, depth, type (gravel or bedrock), and materials at various depths. Locations are suspect; ~11% had E911 or GPS locations in 2006; 17% have updated E911 or GPS locations in 2014.

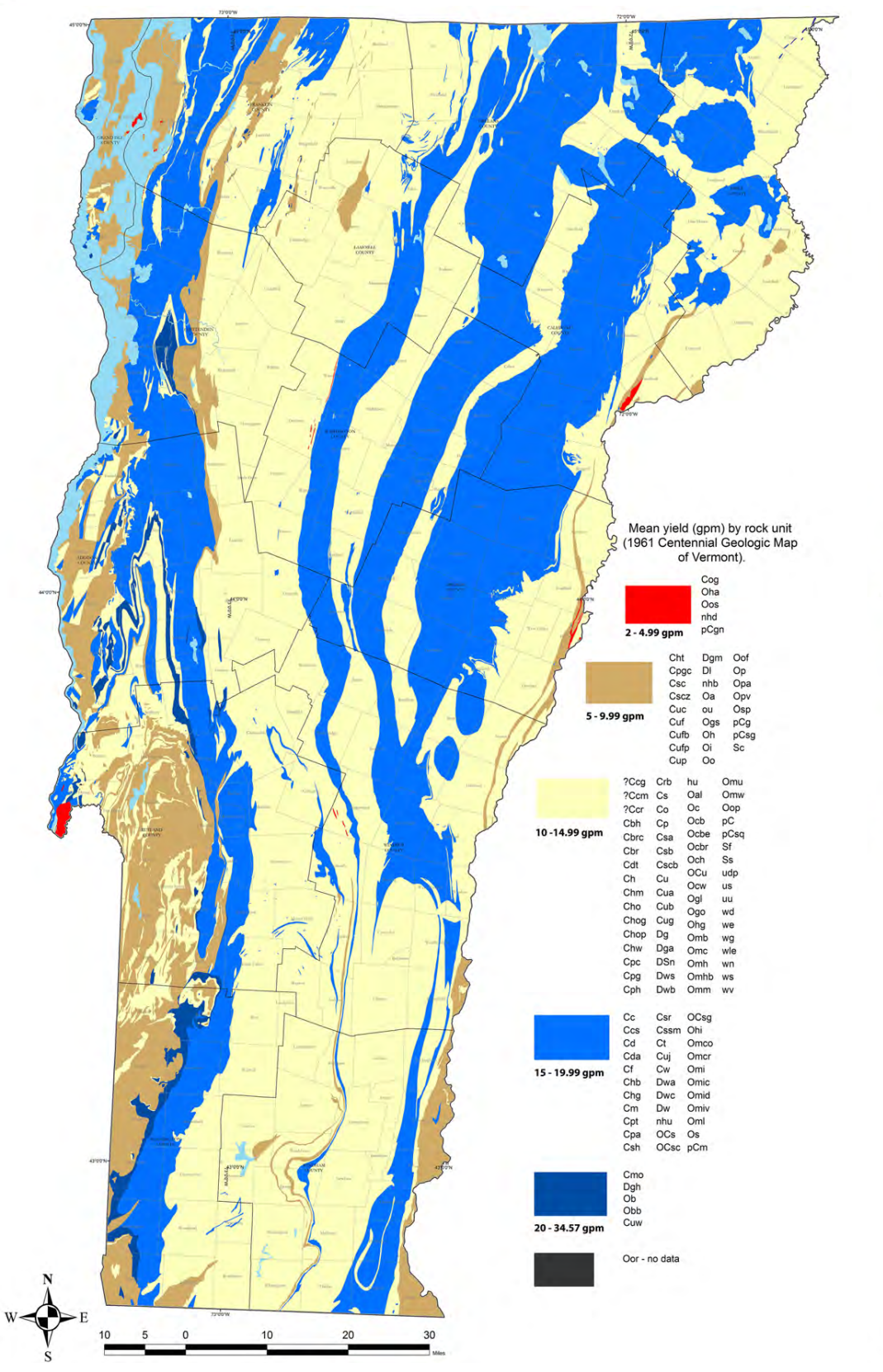


FIGURE 3. Wells were selected and average yields were calculated by bedrock formation (1961 map of Vermont). Formations were then grouped to produce a generalized yield map. Moore and others (2002) discussed factors which correlated negatively and positively with well yield. Among these are year drilled, drilling method, thickness of overburden, depth, elevation, proximity to streams, and type of bedrock.

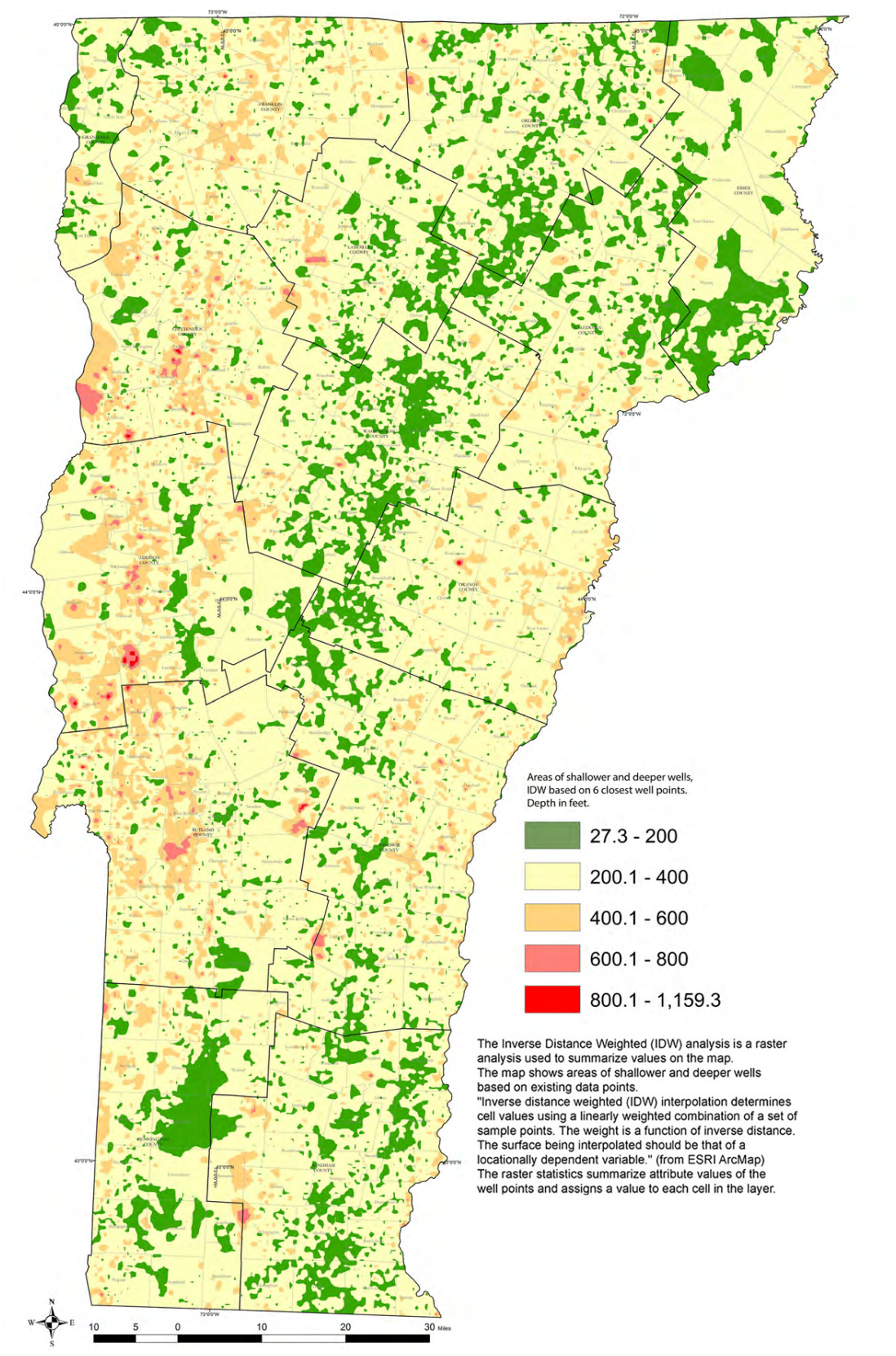


FIGURE 4. Inverse distance weighted (IDW) analyses of well depths based on 6 nearest points. Map indicates some areas where deeper wells could be anticipated. There are large areas of no data (see Fig. 2).

Depth in feet	# of wells	Mean yield in gpm
Well depth ≤ 200'	31340	18.43
Well depth > 200' and ≤ 400'	41179	13.15
Well depth > 400' and ≤ 800'	19142	7.64
Well depth > 800'	654	6.90

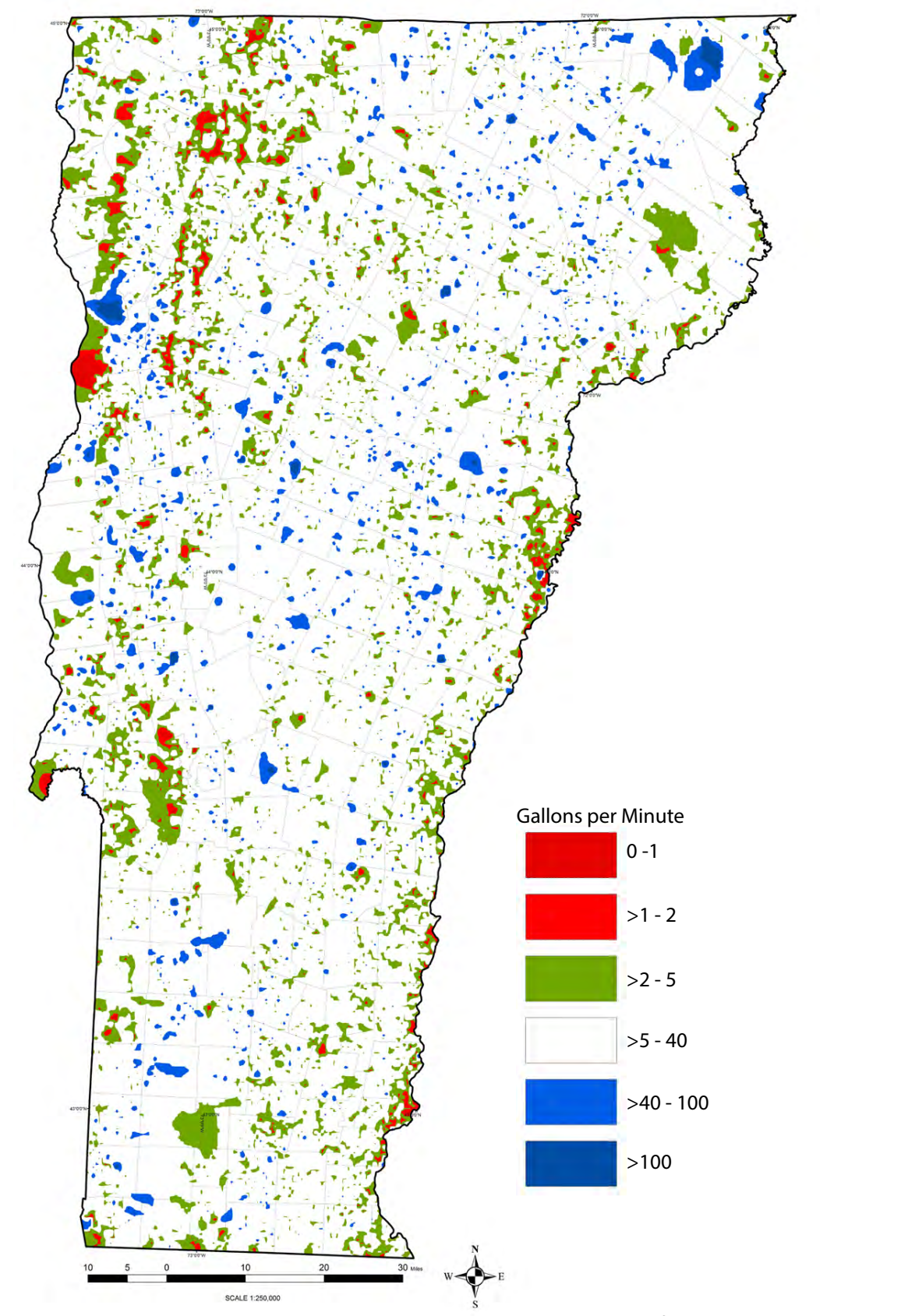
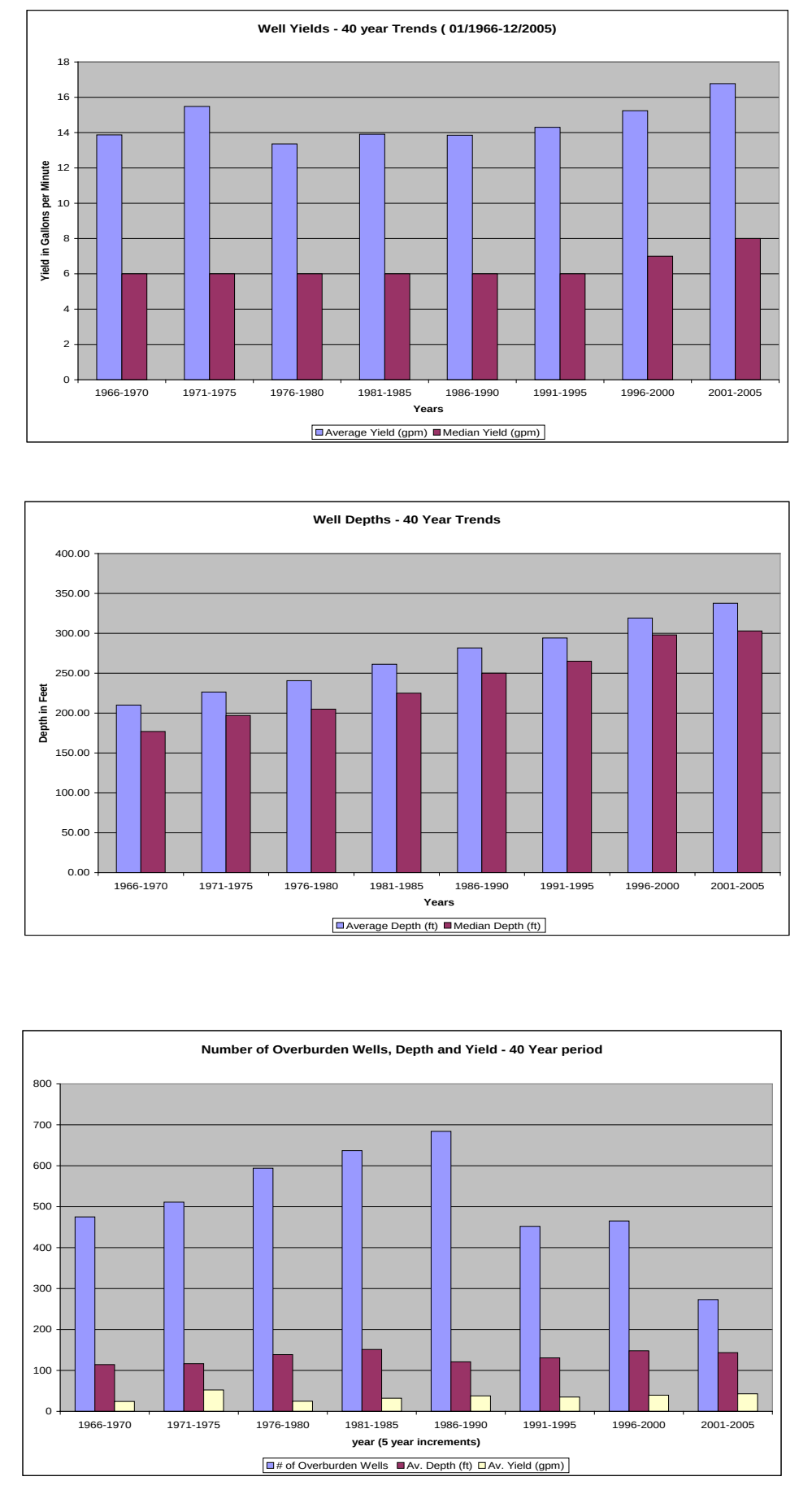


FIGURE 5. Inverse distance weighted analyses (IDW) of well yield based on 6 nearest points. Map indicates some general areas where higher or lower yields could be anticipated. There are large areas of no data (see Fig. 2).

A reported well yield of 1 gpm was selected as the high value for low yield wells; actual yield may be much less. 1 gpm is 1440 gallons per day and the average person uses 75 gallons per day. The percent of low yield wells is 14% and 28% have a yield of >/=20 gpm.

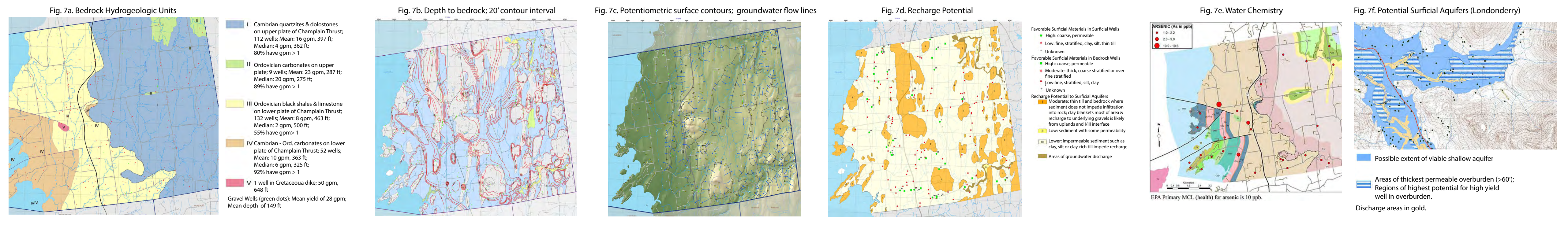
FIGURE 6. 40 Year Well Data in 5 Year Increments



	Overburden Wells	Bedrock Wells
Percent of total wells completed	4.5%	95.5%
Mean GPM	36 gpm	14 gpm
Mean Depth	133 ft	290 ft
Mean GPM/Foot	0.27	0.05

Overburden thickness (ft)	# of Wells	Mean GPM	St. Dev.	Max GPM	Mean Depth (ft)	St. Dev.	Max Depth (ft)
≤10'	34406	12.5	22.2	1200	296.7	165.0	1765
> 10' and ≤ 50'	36016	13.5	21.2	735	282.7	154.4	1485
> 50' and ≤100'	13843	15.3	24.9	1041	286.9	148.9	1465
>100'and ≤300'	7772	17.4	27.5	725	328.1	147.9	1205
>300'	278	19.5	30.4	200	502.3	139.7	1000

FIGURE 7. TOWN AND QUADRANGLE PROJECTS (1:24000 scale)



Expanding on approaches developed with De Simone (2004, 2006, 2008), we generated a series of groundwater resource maps for towns. Maps 7a - 7d are for the Town of Charlotte; 7e is for Londonderry. The maps include: bedrock units as hydrogeologic units (7a), thickness of overburden (7b), general groundwater flow directions and potentiometric surface contours (7c), recharge potential (7d), summaries of located wells and associated data, fracture data and other major structure influences, geochemistry of bedrock, water chemistry of selected wells (7e), potential surficial aquifers (7f) and other town-specific products. A preliminary Hydrogeologic Classification code for surficial materials was developed as part of the Charlotte mapping project (7d). In addition, Kim and others (2014) pursued analyses of water chemistry and the relationship to regional structures and bedrock lithology.

FIGURE 8. WELL INTERFERENCE STUDY (VT Rural Water, 2009)

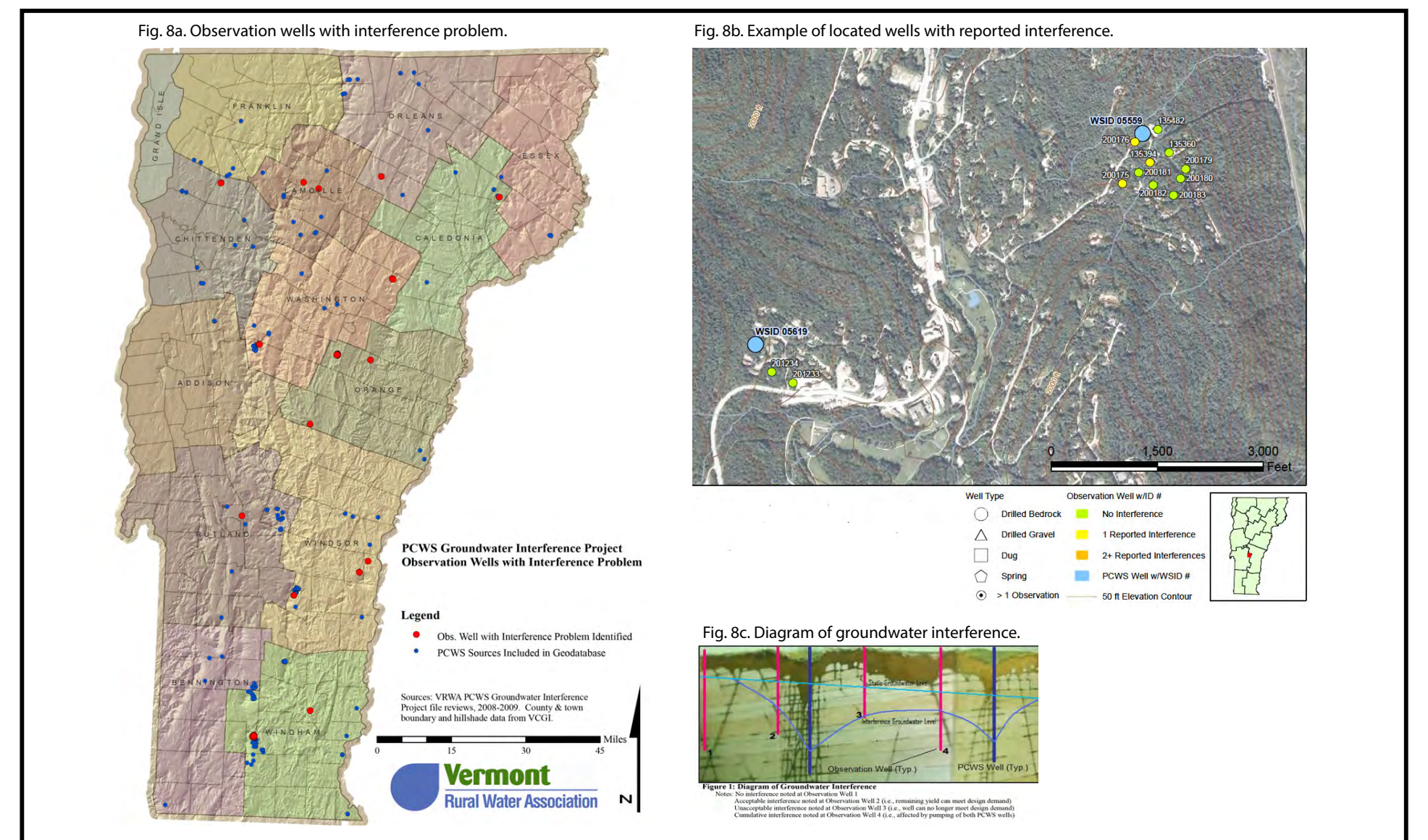


Fig. 8a. Observation wells with interference problem.

Fig. 8b. Example of located wells with reported interference.

Fig. 8c. Diagram of groundwater interference.

Figures 8a, 8b, 8c. The Vermont Rural Water Association (VRWA) assessed groundwater interference caused by the pumping of Public Community Water Supply (PCWS) sources. 203 PCWS sources and 1,082 observation points were evaluated. VRWA concluded that groundwater interference (Fig. 8c) is not a chronic problem although there were 53 instances of unacceptable interference. Some interference was noted in 25% of the observation wells (Figure 8a) and 74 wells showed cumulative interference.

Most wells are completed in fractured bedrock and interference with nearby wells is difficult to predict unless it is directly measured. VRWA reviewed source evaluation reports and developed a database of information for the pumped wells and observation wells. The GIS database and 6 linked tables include pumping test information (duration, water levels, discharge, drawdown etc.), transmissivity calculated in square feet per day, permitted yield, interference noted at observation wells, and a determination of acceptable versus unacceptable interference (Figure 8b).

On a statewide basis, the areas with documented interference could be used to indicate areas for future study and areas to be evaluated for cumulative interference when permitting new wells. We are investigating ways to extrapolate site specific data to a more regional scale in combination with surficial and bedrock lithology and structure.

FIGURE 9. USGS WATER WELL USE STUDY (Medalie and Horn, 2010)

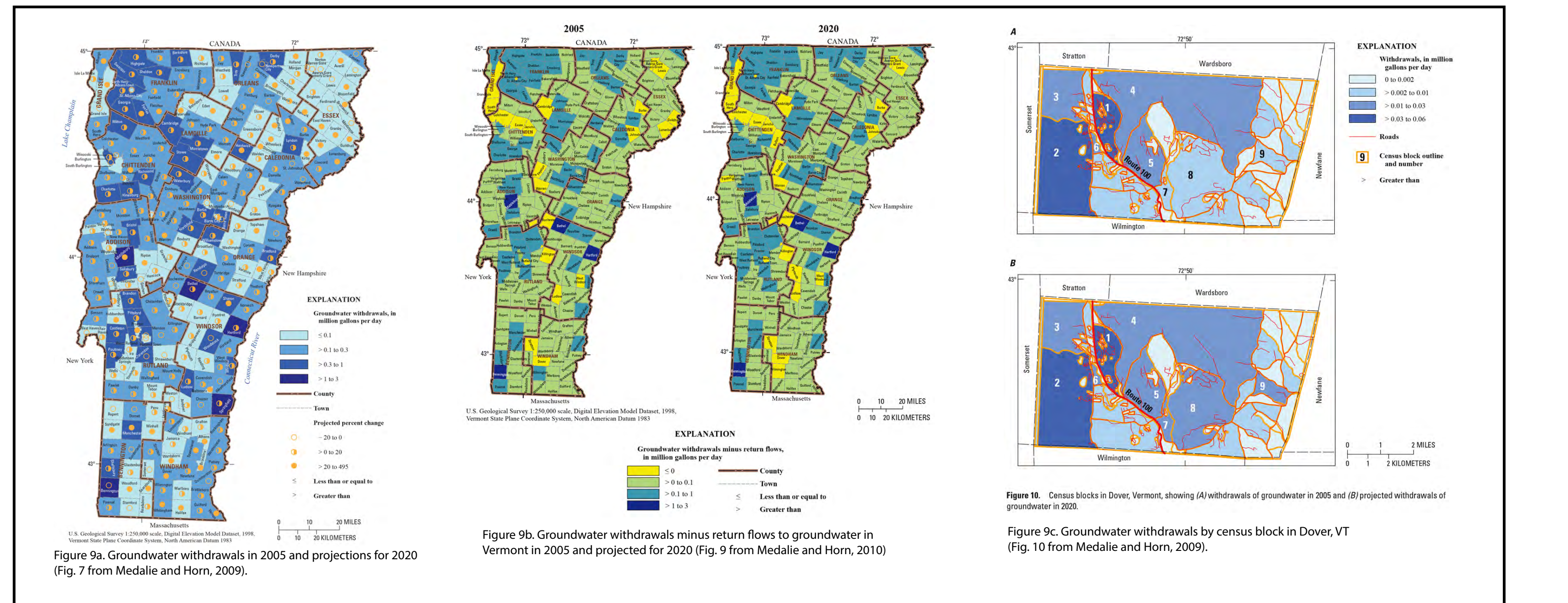


Figure 9a. Groundwater withdrawals in 2005 and projections for 2020 (Fig. 7 from Medalie and Horn, 2009).

Figure 9b. Groundwater withdrawals minus return flows to groundwater in Vermont in 2005 and projected for 2020 (Fig. 9 from Medalie and Horn, 2010)

Figure 9c. Groundwater withdrawals by census block in Dover, VT (Fig. 10 from Medalie and Horn, 2009).

FIGURES 9a-9c. Medalie and Horn (2009), in cooperation with the Vermont Geological Survey, assessed groundwater and surface water withdrawals and return flows in Vermont. Projections of population growth were used to estimate future water resource use and to develop a series of statewide maps and a database which could be applied for planning. Maps show areas of use and growth by town, watershed, and statewide. Tabular data is industry and site specific and facilitates planning for industrial, agricultural and individual land use. Geospatial data and six tables which can be linked to it were developed. The dataset allows for detailed census block analyses (Figure 9c).

In 2005, 12% or 51 million gallons per day of water withdrawals were from groundwater sources. If surface water withdrawal by Vermont Yankee is excluded, groundwater withdrawals rise to 51% of the total. Total groundwater withdrawal in 2020 is projected to be 55.05 million gallons per day.

The VGS is using the digital data to highlight priority areas for future detailed mapping (see Figure 14) and other studies aimed at understanding and protecting water resources. Analyses at the census block level may be completed on a town, county or watershed basis.

FIGURE 11. HYDROGEOLOGICAL CLASSIFICATION

The purpose of this classification is to assist in discerning areas underlain by surficial materials that have some favorability as surficial aquifers. It is intended to be implemented as an interpretation of water well or boring logs, viewed in the GIS in conjunction with the digital version of the 1970 Surficial Geologic Map of Vermont and digital soils data. This classification is based the coarseness of the surficial materials, with the assumption that groundwater will be able to flow easier through coarser materials than through finer ones*. Differences in sorting between the units could, however, negate this assumption. Potential aquifers that have finer-grained materials overlying coarser-grained ones are separated out because the finer-grained and probably less-permeable upper unit may provide protection from direct infiltration of surface waters. Hydrogeologic classes have been assigned to materials in located well logs with reported overburden thicknesses greater than 40'. 11,994 well logs were reviewed.
*Some hydraulic conductivity values for Vermont materials are reported in Figure 11e, a compilation of data collected by consultants while siting landfills.

Hydrogeologic Classification
0 Thick, coarse-grained, stratified deposits over till over coarse-grained stratified deposits.
1 Fine-grained stratified deposits over coarse-grained stratified deposits.
2 Fine-grained stratified deposits over coarse-grained stratified deposits over fine-grained stratified deposits or till.
3 Thick, coarse-grained, stratified deposits over fine-grained stratified deposits over coarse-grained stratified deposits.
4 Sand-matrix till over coarse-grained stratified deposits.
5 Silt-to-clay-matrix till over coarse-grained stratified deposits.
6 Thick, coarse-grained, stratified deposits.
7 Thick, coarse-grained, stratified deposits over fine-grained stratified deposits and/or till.
8 Thick section of sand-matrix till.
9 Thick section of silt-to-clay matrix till over fine-grained stratified deposits.
10 Thick section of fine-grained stratified deposits over silt-to-clay-matrix till or directly over bedrock.
11 Thick section of silt-to-clay-matrix till.
12 Thin surficial deposits or no surficial deposits overlying bedrock. Includes the very common case of thin till over bedrock. Generally less than 40 feet thick.
13 Other. Commonly, this is a thick section of surficial deposits with no details of stratigraphy or highly variable stratigraphy.

Fig. 11a. Dense till

Fig. 11b. Fluvial gravel over sand

Fig. 11c. Laminated silt and sand

Well Depth	Yield GPM	Elevation_DEM	Static Water Elevation	Layer 1	Layer 2	Layer 3	Hydrogeologic Class
60	75	512	502	0.00 wet gravel	10.00 grey wet silt	35.00 hard coarse gravel	1
90	10	393	378	0.00 sand and gravel	20.0 sand and clay mixed	78.00 coarse gravel	3
117	12	1190	1190	0.00 clay & boulders	100.0 gravel		4
80	100	689	679	0.00 sand & gravel, clay & hardpan w/sm boulders	30.0 blue clay w/sand mixed	70.00 gravel	5
111	10	567	507	0.00 dirty gravel	24.0 Sand	100.00 gravel	6
225	30	1128	1098	0.00 silt sand	20.00 gravel clay	50.00 hardpan	8
275	0	899	899	0.00 sand	15.00 clay and hardpan		11

Figure 11d. Examples of materials as reported in the water well database and the assigned hydrogeologic class. The class is based on regional and site specific geologic knowledge, properties of the materials, and surficial maps of the area.

Summary of Horizontal Hydraulic Conductivities for Sites in 6 towns in Vermont				
Depositional Environment	**Material**	**Horizontal Hydraulic Conductivity (ft/day)**	**Number Measured**	**Town**
Coarse lake bottom and deltaic	Gravels	150 to >250	See report	Bristol
	Coarse sand	60 to 200	See report	Bristol
	Medium to coarse sand	15.9	1	Moretown
	Medium to fine sands	60 to 175	3	Eden
	Medium sand	10 to 60	See report	Bristol
	Fine sand	1 to 30	See report	Bristol
	Deltaic sediments: mainly sand & silt	1.1 to 56.7	> 8	Hyde Park
Intermediate lake bottom	Fine to very fine silty sand	0.2 to 9.0	9	Moretown
	Fine sand to silt	0.165 to 5.	10	Williston
	Fine sand, silty sand, silt, minor clay	0.01 to 1.	7	E. Montpelier
Fine lake bottom	Lacustrine silt to clay	0.002 to 0.029	3	Williston
Mixed	Lacustrine sand and ablation till	135	1	Eden
Tills	Sandy ablation till	22	1	Eden
	Till	1	3	Bristol
	Probably till	0.3	1	Hyde Park
	Till (dense)	0.002 to 0.029	3	Williston

Figure 11e. The depositional environment in the above table was interpreted from available surficial geologic maps and consultants' reports associated with permitting of landfills. The "lake" materials are interpreted to be from late Pleistocene proglacial lakes (glaciolacustrine). The lake bottom deposits are mostly very fine sands, silts, silty clays and clays. Lake sand refers to either coarse-grained lake bottom deposits or shoreline or delta deposits. When present in a single vertical profile the sands overly the finer materials.

FIGURE 12. THICKNESS OF SURFICIAL MATERIALS

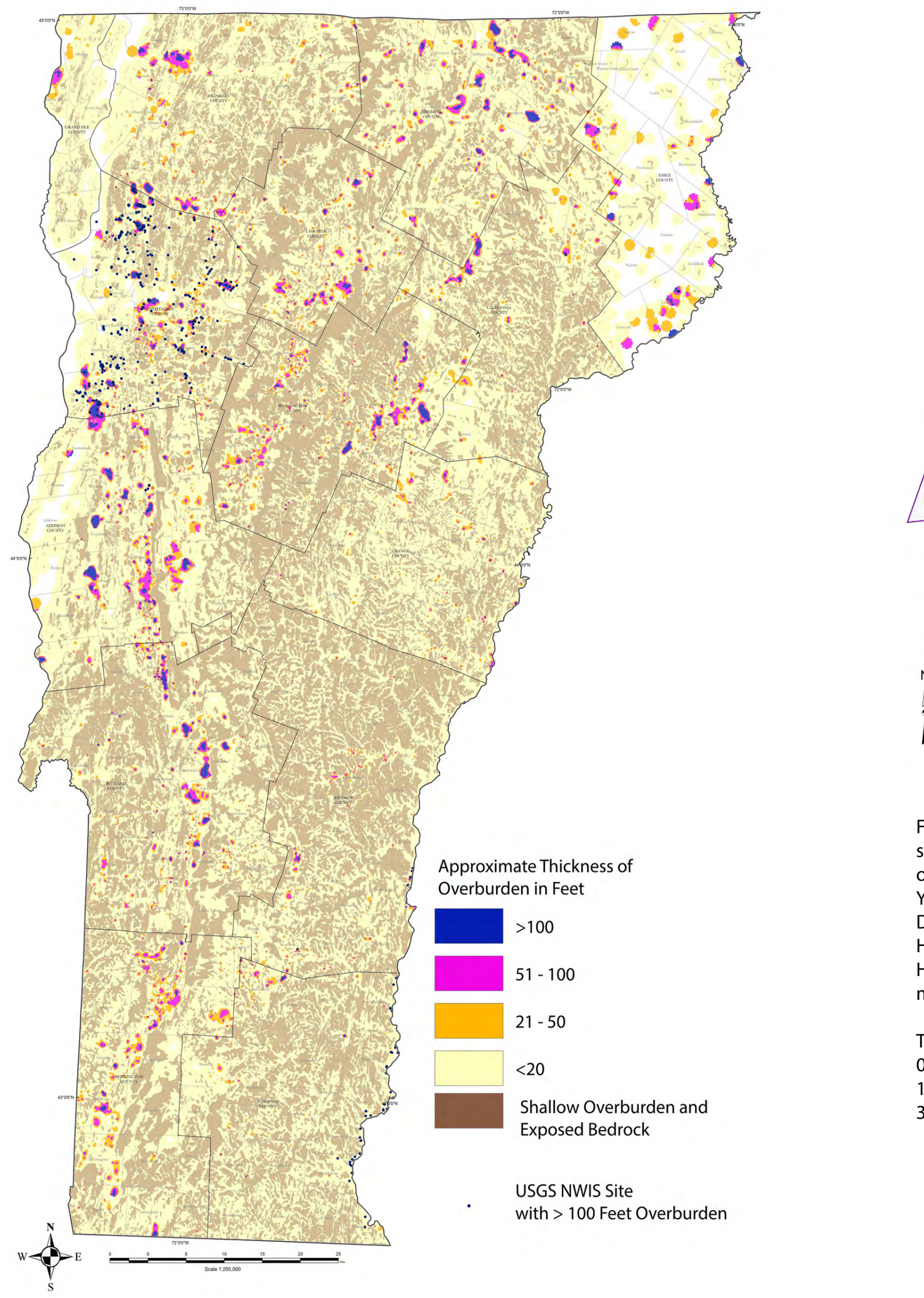


Figure 12. Thickness of overburden was produced by combining: 1) reported thickness for 11,492 located bedrock wells, 2) 141 wells reported as ending in surficial materials and with casing length >100', 3) areas of shallow overburden derived from USDA NRCS Soil Surveys, Surficial Geologic Map of Vermont, and highway outcrops from Eliassen and Springton (2007). Raster files were merged and converted to a point shapefile; the thickness map was generated from the point file using inverse distance weighting. Other areas of thick overburden will be added as more wells are located or as surficial geologic maps are completed.

FIGURE 13. FAVORABILITY MAP

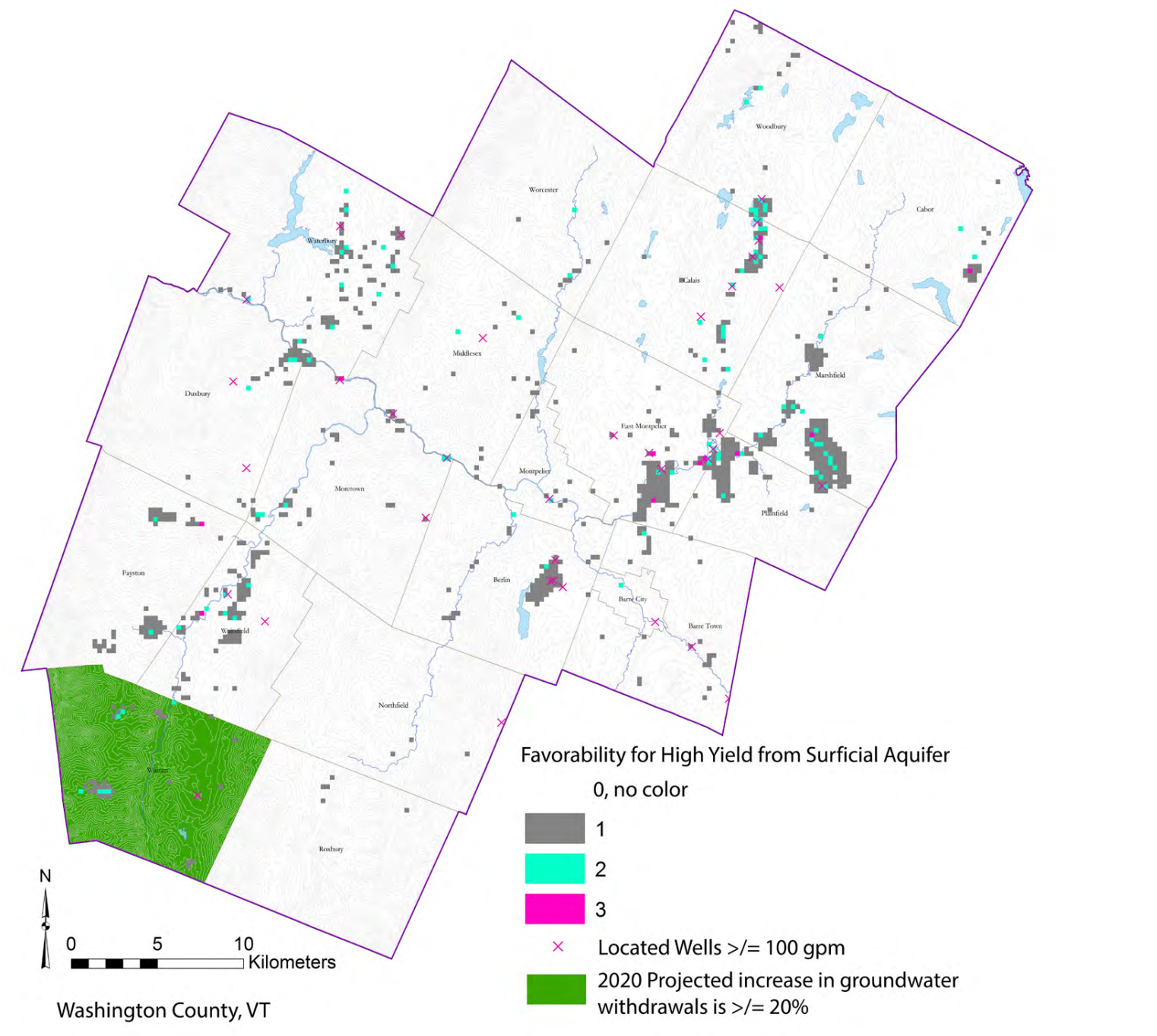


Figure 13 (above). The favorability map for higher yield surficial aquifers is based on summing together three integer rasters derived from yields of surficial wells, depth of overburden, and the hydrogeologic classification. Breaks for the three rasters are:
Yield of surficial wells: 0 = less than 20 gpm, 1 = greater than or equal to 20 gpm.
Depth of overburden: 0 = less than 50 feet, 1 = greater than or equal to 50 feet.
Hydrogeologic classification: 0 = Class 6 through 13, 1 = Class 0 through 5.
Hydrogeologic Class 6 was excluded from the more favorable category as such wells might be susceptible to contamination.

The three rasters are summed together and then ranked as follows:
0: Areas with a raster score of 0 are ranked low favorability
1 - 2: Areas with raster sums of 1 or 2 are ranked progressively higher
3: Areas with a score of 3 are highest favorability

Figure 14 (right) . The statewide map shows the 5 counties where well location projects and assignment of hydrogeologic class have been completed. Well data for 11,994 wells was reviewed for the project. Water well location projects need to be conducted in the remaining 9 counties (~55,000 wells) and hydrogeologic classes could then be assigned to located wells (~ 30%). The raster analysis of thickness could be refined based on the new data and the aquifer favorability maps would be developed by county.

Groundwater use data by town is available for the state and the highlighted areas show towns where growth or increase in use is projected. The map focuses attention on areas where new projects could assist in locating future water supply. The more detailed census block analysis can also be constructed for these towns.

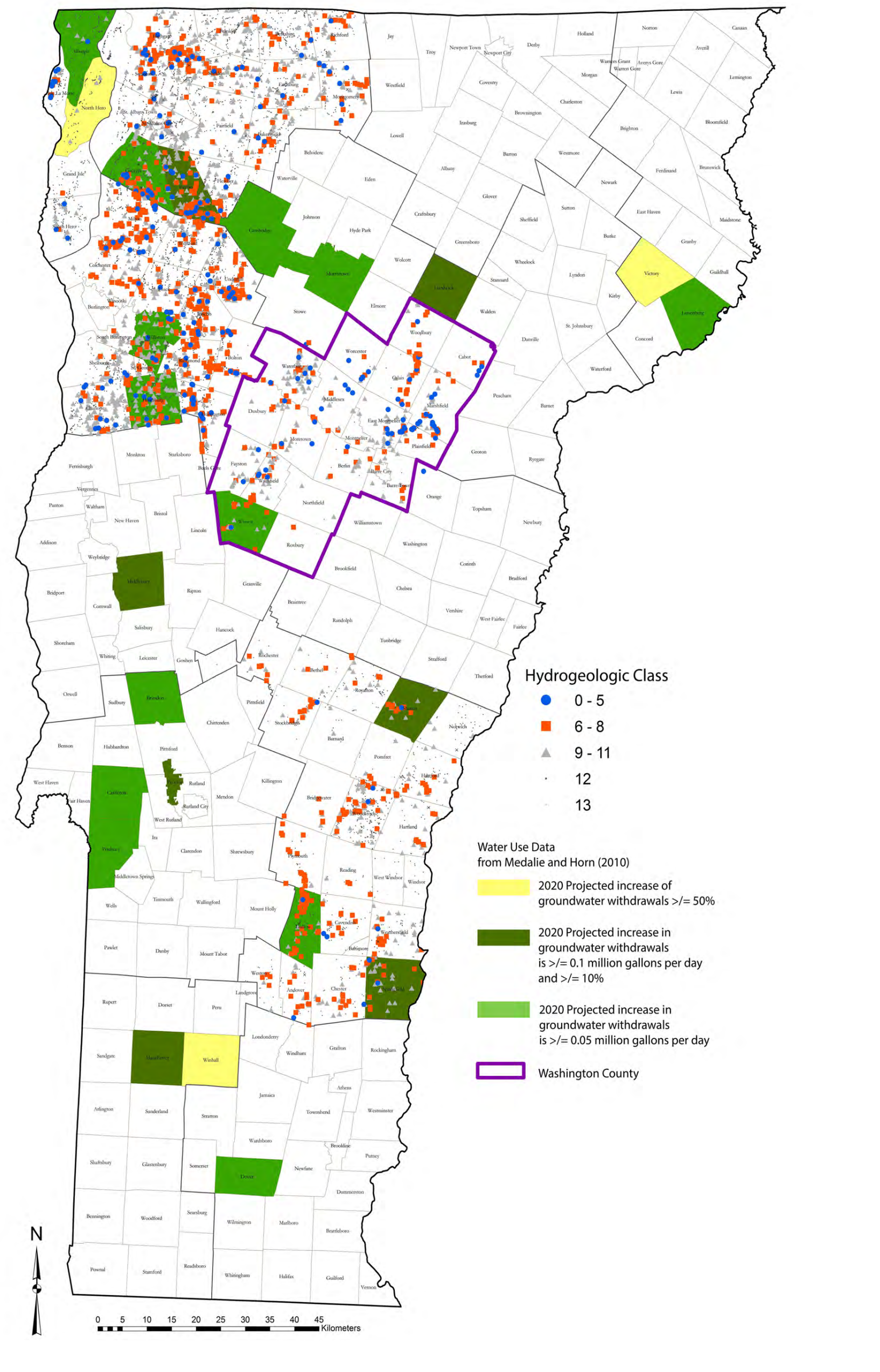


FIGURE 14. STATEWIDE FOCUS

FIGURES 15, 16. COUNTY FAVORABILITY MAPS

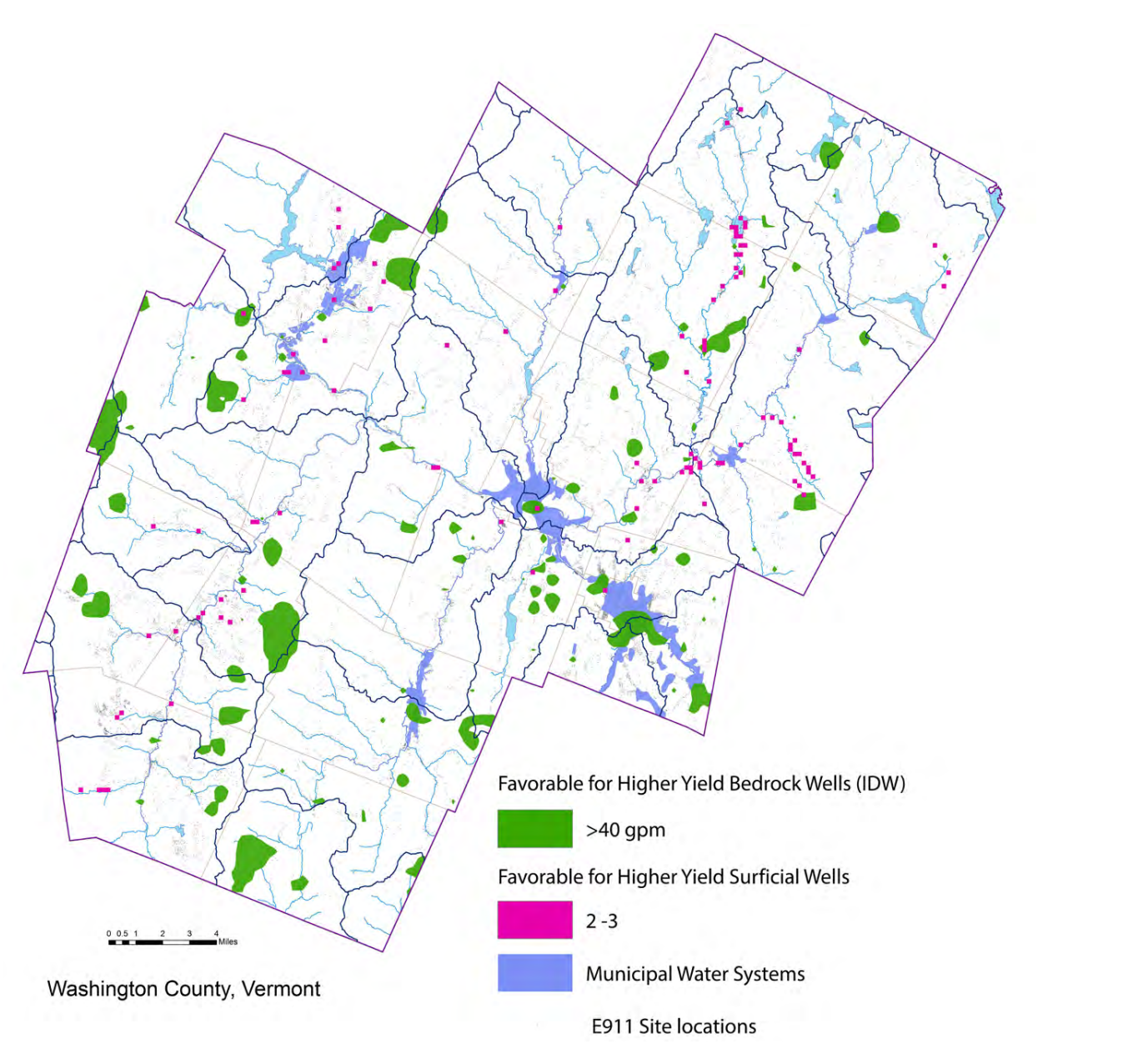


Figure 15. Combining the created GIS datsets allows us to produce general favorability maps by county. This map shows areas favorable for higher yield bedrock wells based on the IDW analysis and for higher yield surficial wells based on the raster analysis. E911 sites show residential and other facilities. Watershed boundaries are shown and may mimic groundwater recharge areas.

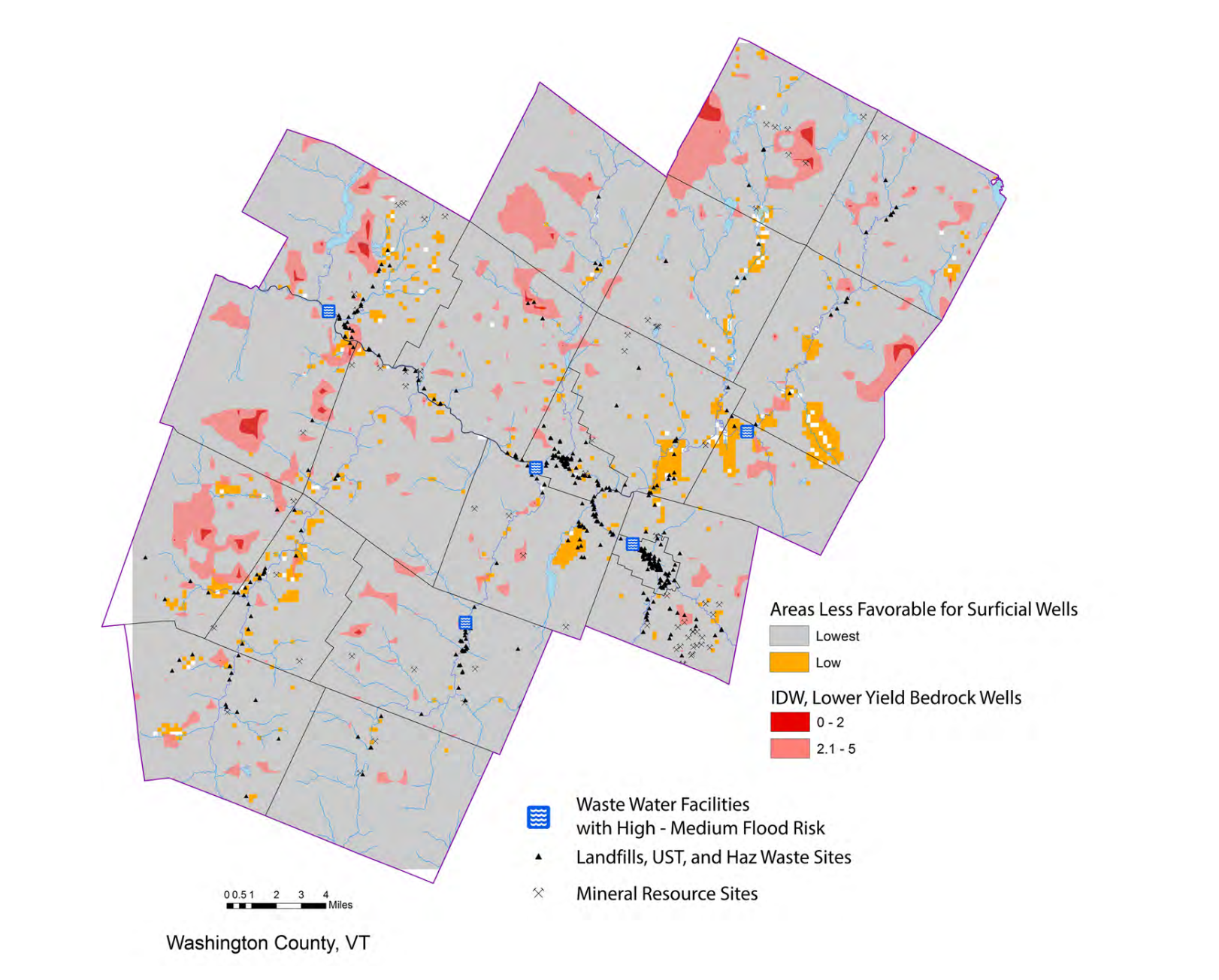


Figure 16. The map shows potential areas of lower favorable yield and includes areas with potential water quality issues. Similar maps for areas of projected deep wells could be produced. Although not shown here, other digital coverages such as brownfields sites, source protection areas, and water sources with elevated elements of concern (i.e. arsenic, radioactivity) will add to the overall analysis of groundwater resources.

CONCLUSIONS:

The Vermont ANR water well database, with 101,041 records and 76 fields is a powerful dataset for evaluating groundwater resources. Although some data clean-up has been done, many errors remain in reported numbers. Locations are reliable for 16,913 out of 101,041wells and we anticipate that improved locations could be linked to approximately 35% of the records. Continuing to locate more wells and link the data to the accurate locations will strengthen the analyses. Development of statewide maps would follow with enhanced thickness maps, refined bedrock well analyses, and statewide raster analyses for favorable surficial aquifers.

We have done limited analyses of other fields in the water well database. The wells drilled as "deepened or replaced existing" wells are of interest since 21,362 or 21% of all wells fall in these categories. The wells may replace old dug wells, replace a failed well, be desirable for a new development, or perhaps be indicative of water supply problem areas.

We are interested in developing groundwater resource data by watershed, in conjunction with our more detailed 1:24,000 scale map projects and geochemistry data. Communication of groundwater resources data to the general public, towns and regional planners is an important step in protection and use of the resource.

Other data to develop on a statewide scale:
a) Major structures: compare upper and lower plates of thrust faults, proximity to normal faults etc.
b) Fracture data distribution/density and orientation
c) Bedrock chemistry
d) Overburden chemistry
e) Water chemistry, particularly elements of concern
f) Reported nuisance issues such as staining and odor
g) Water use on a town scale
h) Deepened existing/replace existing wells as indicators of potential yield problems
i) Static water levels and recharge areas

REFERENCES:

De Simone, D., 2004, Surficial geology and hydrogeology of Manchester, Vermont: Vermont Geological Survey Open File Report VG04-1, scale 1:24,000.
De Simone, D., 2006, Surficial geology and groundwater resources of Woodstock, Vermont: Vermont Geological Survey Open File Report VG06-5, scale 1:24,000.
De Simone, D. and Gale, M., 2008, Surficial geology and hydrogeology of the town of Londonderry, Vermont: Vermont Geological Survey Open File Report VG08-2, scale 1:24,000.
Doll, C. G., ed., 1961, Centennial Geologic Map of Vermont: Vermont Geological Survey, Montpelier, VT, scale:1:250,000.
Doll, C. G., ed., 1970, Surficial Geologic Map of Vermont: Vermont Geological Survey, Montpelier, VT, scale:1:250,000.
Eliassen, T. and Springston, G., 2007, Rockfall hazard rating of rock cuts on US and State highways in Vermont: Research Project RSCH010-974, Report 2007-16, VT Agency of Transportation, Materials and Research Division, Montpelier, VT, 31 p.
Gale, M., Springston, G., Knox, P. and Becker, L., 2009, Statewide analyses of bedrock water well data: Vermont Geological Survey Open File Report VG09-8, 7 plates, scale 1:250,000.
Gale, M., Kim, J., Earle, H., Clark, A., Smith, T. and Petersen, K., 2009, Bedrock geologic map of Charlotte, Vermont: Vermont Geological Survey Open File Report VG2009-5, scale 1:24,000.
Hanson, E., 2009, Public community water systems groundwater interference project: Vermont Rural Water Association Report to the Vermont Agency of Natural Resources, Montpelier, VT.
Kim, J.J., Ryan, P., Klepeis, K., Gleeson, T., North, K., Davis, L., Bean, and Filoon, J., 2014, Tectonic evolution of a Paleozoic thrust fault influences the hydrogeology of a fractured rock aquifer, northeastern Appalachian foreland: Geofluids, doi:10.1111/gfl.12076.
Medalie, L. and Horn, M.A., 2010, Estimated water withdrawals and return flows in Vermont in 2005 and 2020: U.S. Geological Survey Scientific Investigations Report 2010–5053, 53 p.
Moore, R.B., Schwarz, G.E., Clark, S.F. Jr., Walsh, G. J., and Degnab, J.R., 2002, Factors related to well yield in the fractured-bedrock aquifer of New Hampshire: USGS Professional Paper 1660.
Springston, G., Gale, M., Kim, J., Wright, S., Earle, H., Clark, A., Smith, T., and Petersen, K., 2010, Hydrogeology of Charlotte, Vermont: Vermont Geological Survey Open File Report VG10-1, scale 1:24,000.