



# USING GAS PRODUCTION AND PRODUCED WATER TRENDS TO EXPLORE MARCELLUS FORMATION DEVELOPMENT IN PENNSYLVANIA



## ABSTRACT

Since the start of the shale gas boom in Pennsylvania, there has been considerable debate regarding both the volume of recoverable gas and produced water associated with the Marcellus Formation and other domestic hydrocarbon-bearing shale formations. PADEP's Bureau of Oil and Gas Planning and Program Management has tallied the cumulative and semi-annual gas production data for all Marcellus Formation gas wells that have been on-line since 2005. The production data were downloaded and subsequently analyzed to determine when the wells first came on-line in order to allow new well production to be distinguished from existing well production. This analysis assists in determining if more recent drilling and stimulation practices are increasing gas yields at wells.

Produced water trends were also assessed for a subset of the wells in order to develop a predictive tool for informing future waste management practices. As the field matures, drilling rates will plateau and then decline, but produced water volumes are expected to increase for some time. A reduction in drilling renders the recycling option less viable, making it important to consider alternatives for waters known to contain very high dissolved solids, including barium, in addition to radionuclides. Data were mapped using a Geographic Information System (GIS) to develop a model for better understanding shale gas development in Pennsylvania.

## GAS PRODUCTION & PRODUCED WATER

Annual and semi-annual production and waste reports compiled by PADEP's Bureau of Oil and Gas Planning and Program Management were downloaded from the reporting website. The data were compiled in Excel spreadsheets. Next, the dataset was cross-referenced with the Oil and Gas Well Formation Report database, which allowed data to be selected for wells targeting only the Marcellus Formation. Once the Marcellus Formation wells were isolated, the cumulative production and produced water were tabulated for the period beginning in 2005 and ending in the first half of 2013 (2013-1). Production in thousand cubic feet per day (Mcf/day) was analyzed as a function of time for only the new wells that came on-line during each reporting period. The data indicate that production rates have continued to increase during each subsequent reporting period (Figure 1).

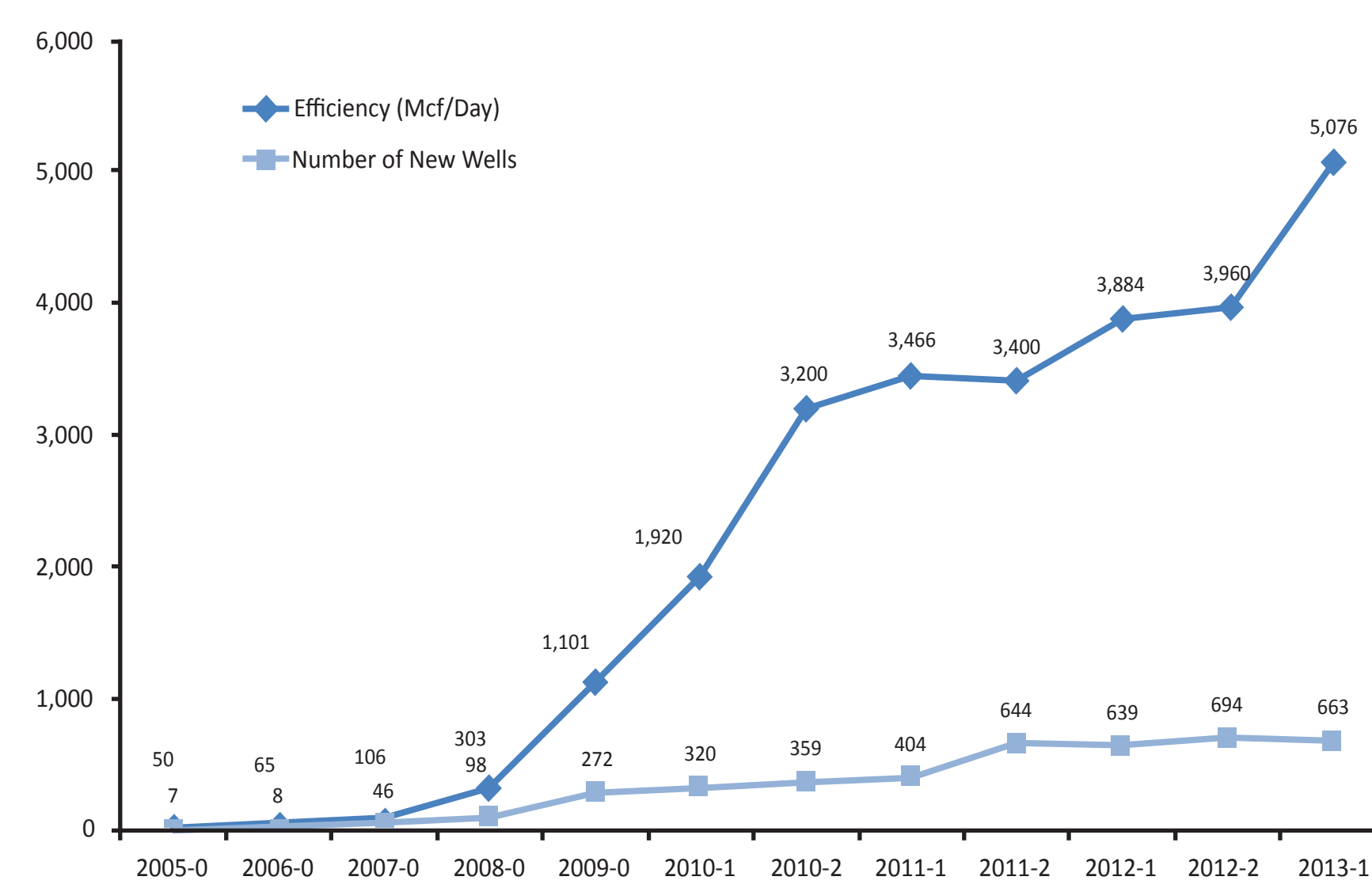


Figure 1 – Marcellus Formation production (Mcf/day) from new wells as function of reporting period compared to number of wells that came on-line during each period.

For produced water, since one objective of the analysis was to determine how much waste is produced by individual wells, data were limited to single wells on a pad, thus eliminating the effect of averaging in the dataset. Cumulative production and produced water for the Marcellus Formation wells for the second half of 2012 (2012-2) and 2013-1 were plotted using ArcGIS software. Data were contoured using the natural neighbor algorithm and clipped to a merged buffer of 2.5 miles around each well site to provide a sense of how the shale play is being drained and to examine for any spatial trends with regard to produced water volumes (Figures 2 and 3). Finally, waste management trends were also summarized for the same group of wells during those reporting periods (Figure 4) (Schmid, personal communication, 2013).

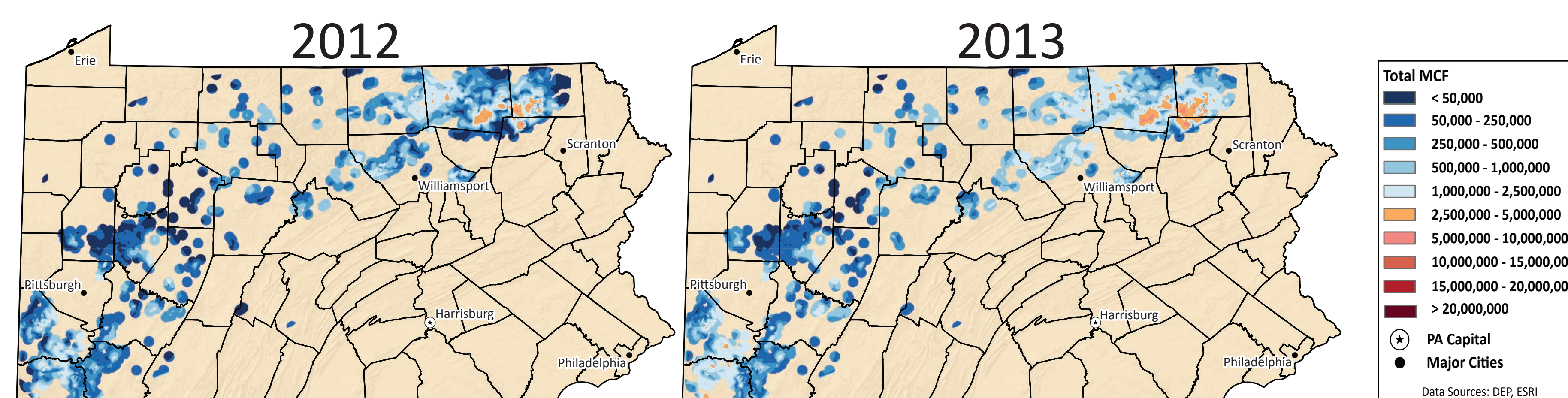


Figure 2– Cumulative production from Marcellus Formation production (Mcf) through the second half of 2012 and first half of 2013 (PADEP, 2013).

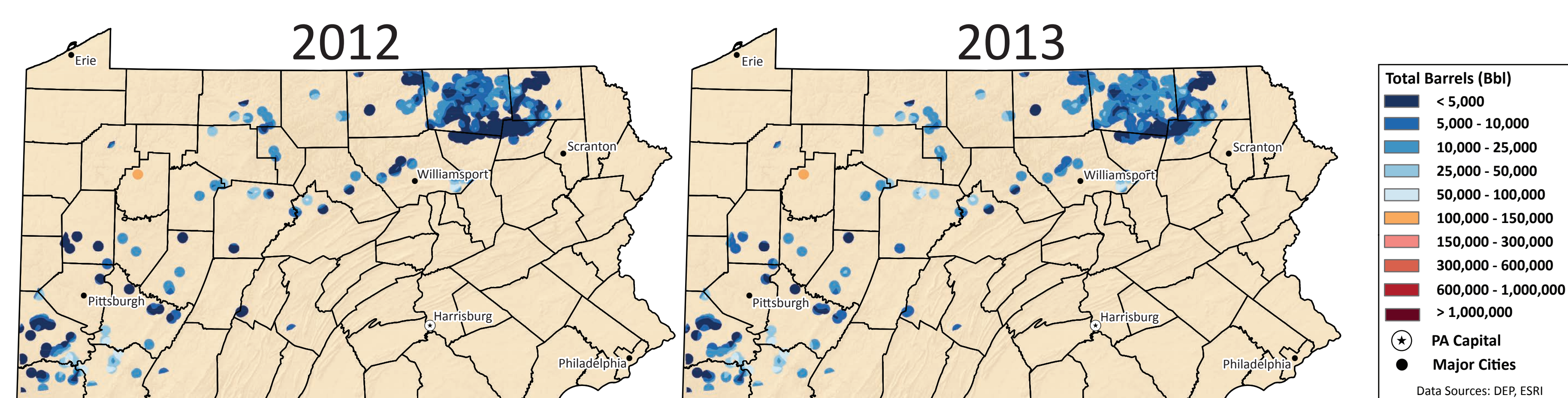


Figure 3– Cumulative produced water volumes (Bbls) from single wells on a pad through the second half of 2012 and first half of 2013 (PADEP, 2013).

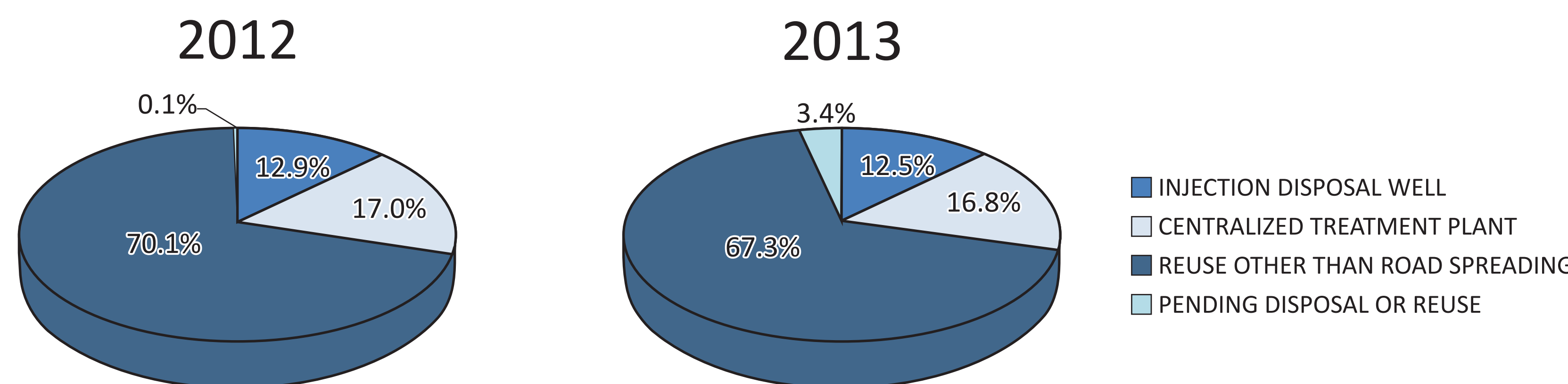


Figure 4– Produced water management trends for waste generated at single wells on a pad during the second half of 2012 and first half of 2013 (PADEP, 2013).

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## PREDICTIVE MODELING OF PRODUCED WATER

Thirty-five horizontal Marcellus Formation completions that have been in production since at least the second half of 2010 (2010-2) were selected. The spatial distribution of the wells provides sufficient coverage throughout the play (Figure 5).

For each of the reporting periods, five (5) independent variables were considered: (1) production time (days); (2) estimated ultimate recovery (Bcf); (3) longitude (dd); (4) latitude (dd); and (5) gas flow (Mcf). In this case, the dependent variable is produced water output (bbls/day). Prior to executing the multiple regression analysis, simple linear regression analyses were completed and normalizing data transformations were applied to improve the goodness-of-fit between variables. Stepwise regression was then completed using SPSS v. 21 and it was found that the most important predictor variables were production time, latitude, and longitude. It should be noted that some spatial autocorrelation is expected in the dataset as evidenced by the importance of latitude and longitude. This is anticipated with most geological datasets. Table 1 summarizes the results of the regression analysis. Figure 6 compares observed to expected outcomes for the regression model.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	R	R Square	Adjusted R Square
	B	Std. Error	Beta			VIF			
5 (Constant)	-529.868	66.795		-7.933	0.000				
Production Time	-1.249	0.089	-0.679	-13.978	0.000	1.044	0.731	0.535	0.528
Longitude (dd)	72.646	8.672	0.891	8.377	0.000	5.009			
Latitude (dd)	60.094	8.332	0.760	7.213	0.000	4.918			

a. Dependent Variable: Produced Water Output (bbl/day)

Table 1 – Results of stepwise multiple regression modeling conducted in SPSS v. 21.

To simulate future produced water trends, well drilling activities were forecasted by first subdividing the likely footprint of the Marcellus Formation play into one (1) square-mile drilling units. The boundaries of the play were approximately defined to the south by the Allegheny structural front and the southern border of the state, to the east by the extent of drilling thus far, to the west by the western border of the state, and to the north by the 3,000-foot structural contour of the Marcellus Formation base and the northern border of the state. It was assumed that within this footprint, urban areas and drilling units with greater than 33% of their area comprised by the floodplain would not be developed. Drilling unit dimensions are 3,000 feet by 9,000 feet with the long axis oriented NW-SE along the trend of the J-2 joint set. Next, the number of wells drilled on each unit was determined and the map of the play was color-coded (Figure 7).

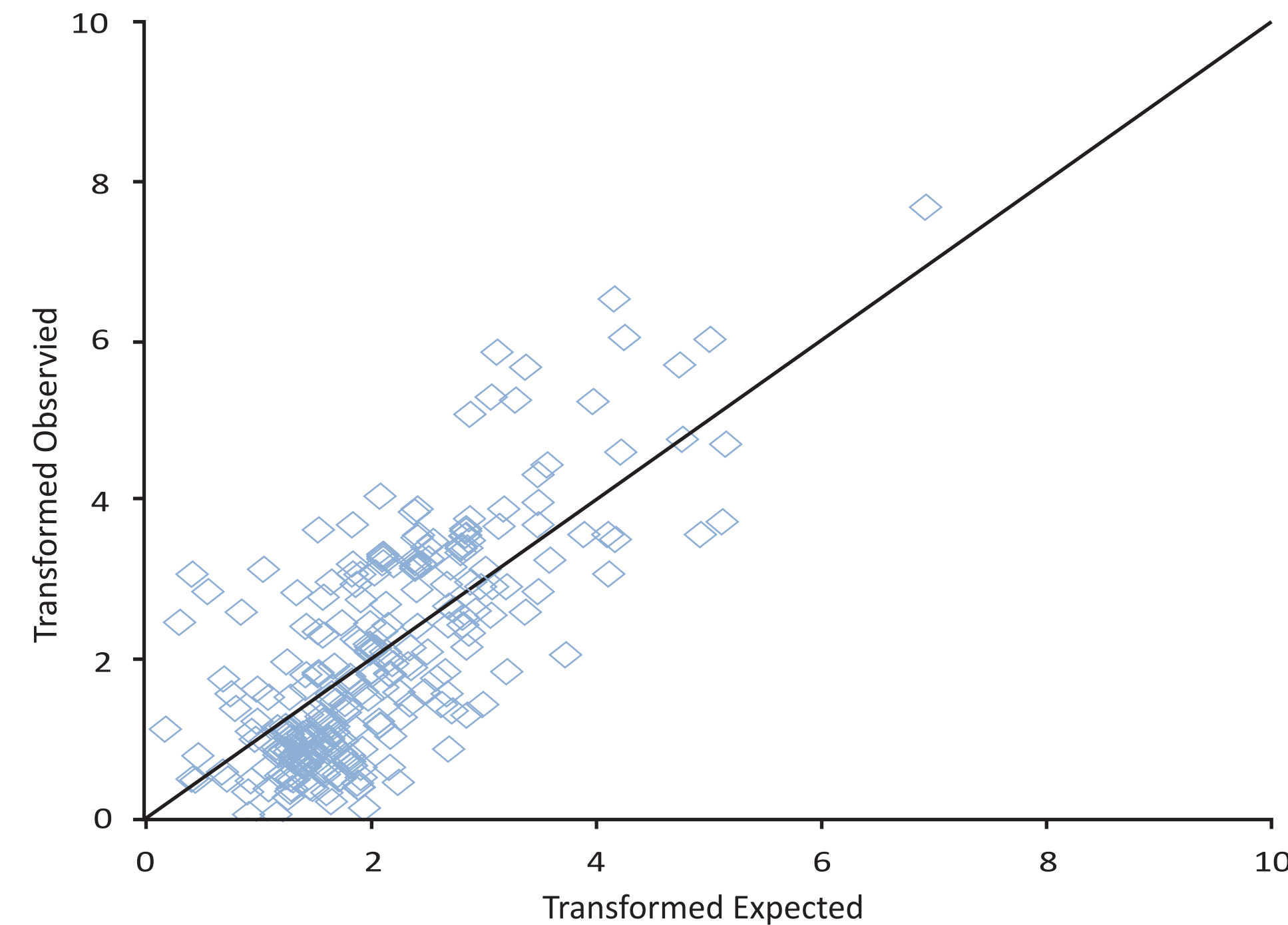
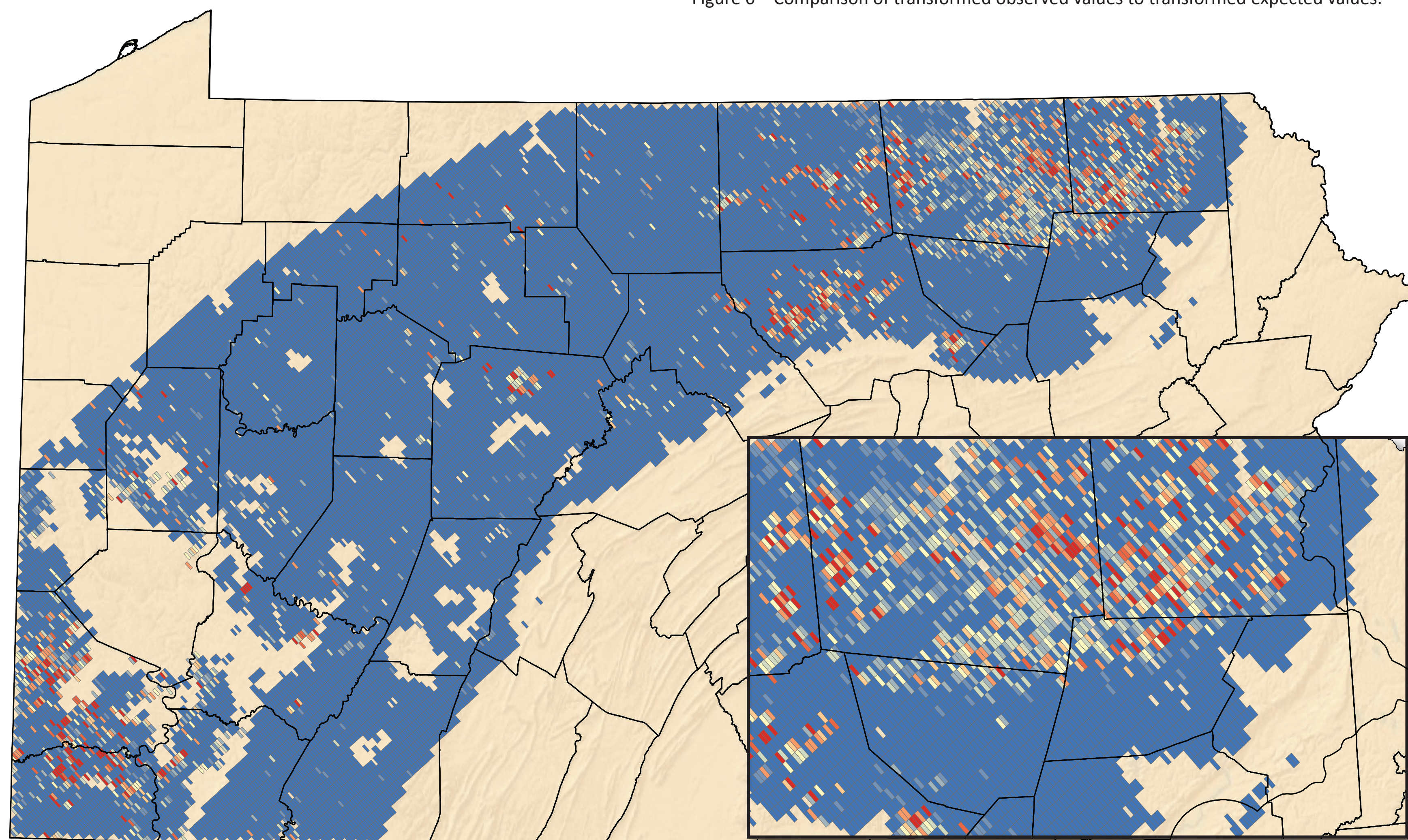


Figure 6 – Comparison of transformed observed values to transformed expected values.



Wells Per Drilling Unit

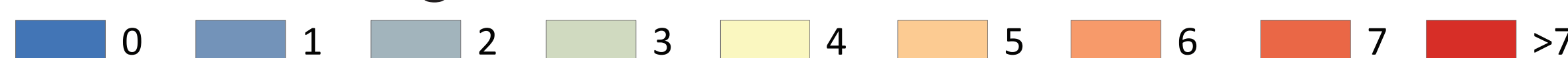


Figure 7 – Spatial distribution of hypothetical Marcellus Formation drilling units in Pennsylvania. Inset map depicts Bradford, Sullivan, Susquehanna, and Wyoming counties.

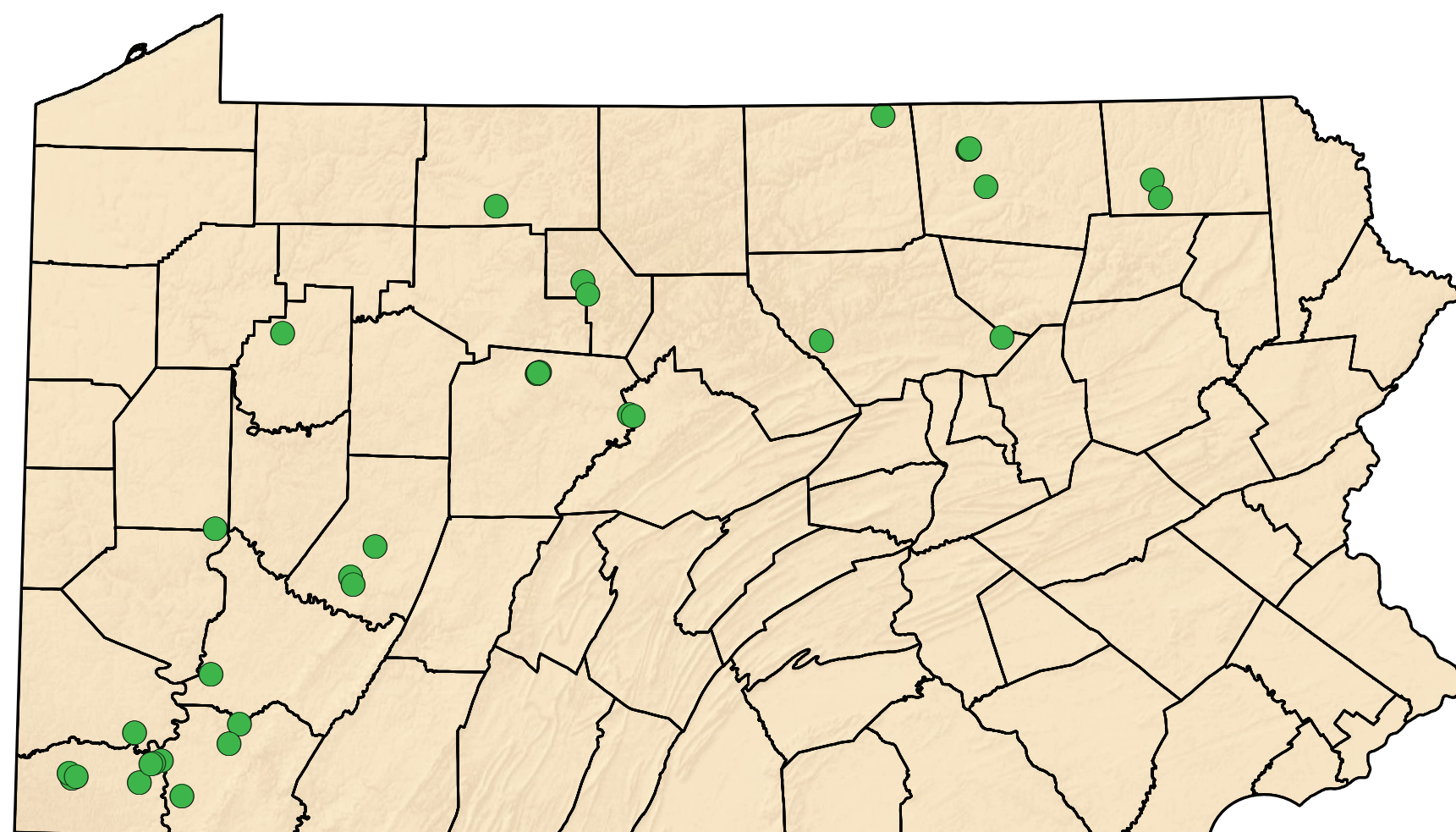


Figure 5 – Spatial distribution of wells used to develop regression model.

It was assumed that eight (8) wells would be drilled on each available unit and that units already containing 8 or more wells were complete. To model future development, available well locations were assigned random numbers and selected using Microsoft Excel's random number generator function. An aggressive development schedule of approximately 3,000 new wells drilled per year was assumed. Coordinates for new wells were either chosen as the mean center of the drilling unit (for drilling units with no development to date) or the average of the coordinates for existing wells on the unit. The drilling simulation was terminated after 30 years.

Using the predictor variables from the multiple regression analysis, produced water outputs were calculated for all active wells as determined by the simulation. Output rates were modeled as a continuous logarithmic function and converted to volumes by multiplying by the number of days in production. For the simulation, it was assumed that all wells came on-line immediately and were produced 365 days per year. The inactive wells in the state were incrementally brought on-line over the first five (5) years of the simulation. It was also assumed that wells would be plugged and abandoned after 20 years and that no wells would be re-stimulated. Different modeling runs were completed to assess uncertainty: (1) base case, (2) 95% LCL, (3) 75% LPL, and (4) 50% LPL (Figure 8).

Model results were calibrated by comparing the different simulations to actual produced water volumes generated between 2010 and 2012. It was found that the 50% LPL and 75% LPL bracketed the actual data most closely. An early peak is recognized due to the significant increase in wells coming on-line at one time, i.e., roughly 1,000 inactive status wells in addition to 3,000 newly drilled wells. The flowback signature, which is most notable during the first year of production, results in this peak. After all the inactive status wells are brought on-line, produced water volumes decrease then slowly increase again until leveling off in 2034. Comparisons to current approximate disposal well capacity in the state and the demand for base fluid considering the simulated drilling schedule were also made (Figure 9). Disposal well capacity was estimated by calculating the average maximum injection rate for all wells currently operating or in the process of being permitted. Base fluid demand was estimated by assuming 4,000,000 gallons of water would be required to stimulate each well in the simulation. It should be noted that the logistics and technical considerations related to recycling base fluid are not contemplated as part of this study. Additionally, the logistics associated with disposal at deep injection well sites were not evaluated either. Proximity to available sites and water quality are two factors that would influence how readily flowback and produced waters could continue to be used for future stimulations. Proximity to disposal well locations is an important variable for determining the economics of deep well injection.

Assuming wastewater management trends remain consistent with those observed during the last half of 2012 and the first half of 2013, it is possible to use the model to determine what volumes of produced water are expected for each waste stream (Figure 10). Applications include injection well disposal network planning, treatment infrastructure development, and recycling infrastructure development.

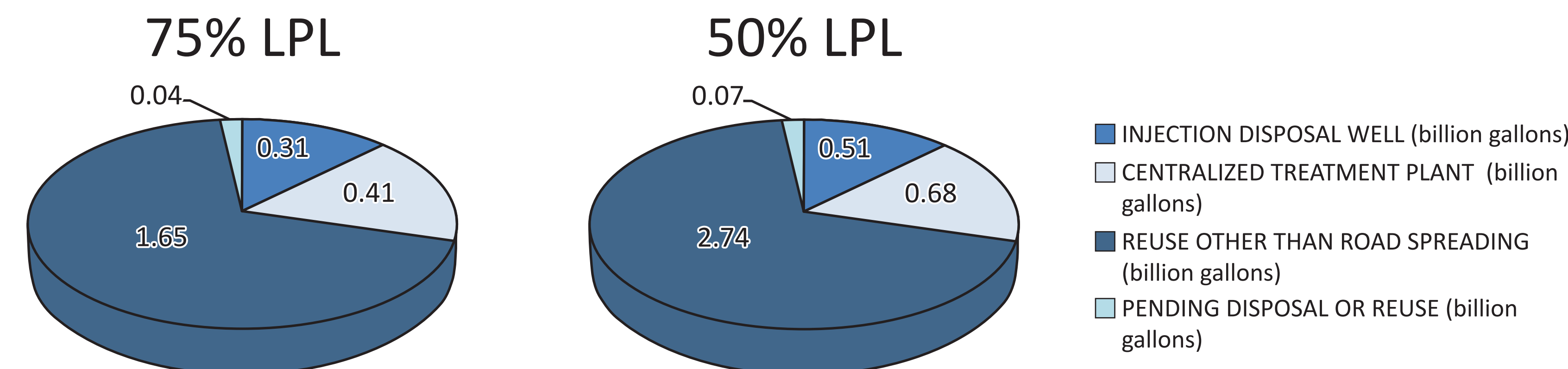


Figure 10 – Predicted waste stream volumes in billion gallons based on present-day waste handling strategies. Analyses are based on 75% LPL and 50% LPL models, respectively. Multiple regression analysis and drilling simulation predicts volumes will plateau at 2.4 and 4.0 billion gallons, respectively, in 2034.

## CONCLUSION

Gas production and produced water trends have been evaluated for the Marcellus Formation in Pennsylvania. Gas production data suggest increasing efficiency of resource development as a function of time, with the greatest quantities of gas having been extracted in the two core areas of development in northeastern and southwestern Pennsylvania. A waste stream assessment shows that the majority of produced water is now being recycled, mostly as base fluid for hydraulic fracturing operations. In comparing the spatial distribution of cumulative gas production to cumulative waste production, it has generally been noted that higher volumes of gas inversely correlate with produced water volumes. It is postulated that more produced water may be present in the Marcellus Formation moving away from the Allegheny structural front, perhaps due to changes in the character of the formation related to post-depositional processes.

A multiple regression model aimed at predicting produced fluid volumes over time was developed. A stepwise analysis was used and identified regressor variables include time in production, latitude, and longitude. The model was used to predict produced water volume as a function of time and results suggest that the volume of wastewater generated will be less than the volume needed for stimulation base fluid. The predictive model may be useful for developing future effective wastewater management strategies, although refinement may be necessary as more data become available.

Sources: PADEP, 2013, oil & gas production reports, <https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Welcome/Welcome.aspx>, accessed December 2013  
Schmid, K., 2013, Personal Communication