

No. 142, Original

In the

Supreme Court of the United States

STATE OF FLORIDA,

Plaintiff,

v.

STATE OF GEORGIA,

Defendant.

Before the Special Master

Hon. Ralph I. Lancaster

**PRE-FILED DIRECT TESTIMONY OF FLORIDA WITNESS
DR. GERRIT HOOGENBOOM**

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I. INTRODUCTION

1. My name is Dr. Gerrit Hoogenboom and I have over thirty years of experience working with farmers and researchers to increase the productivity of farmers' crops while simultaneously reducing the need for irrigation water and other inputs such as fertilizers and pesticides.

2. I have a Ph.D. in Agronomy & Soil Science and a dual Master's degree in Horticulture and Theoretical Production Ecology. I have over thirty years of experience in research, education and outreach in agricultural and environmental engineering with emphasis on the development and application of crop simulation models and decision support systems. My work focuses on the analysis of local conditions (*e.g.* soil, weather, and crop type) using sophisticated computer modeling to provide farmers with options and information to support their agriculture management decisions, such as how much irrigation water to apply.

3. I investigated whether Georgia farmers in the Apalachicola, Chattahoochee, and Flint River Basin (the "ACF Basin") could use less water without reducing the productivity of their crops and negatively impacting their income. I further investigated impacts of using slightly less irrigation water than the optimal amount on crop productivity. My testimony is associated with the research and analysis performed by Dr. David Sunding, an agricultural economist, who demonstrates that Georgia can use less water without reducing the amount of crop, or yield, produced.

4. In this testimony, I describe how changes in the amount of irrigation water applied to the four major crops in the Georgia portion of the ACF Basin impact the productivity of those crops relative to other irrigation scenarios. The four major crops are peanut, corn, cotton and soybean.

5. My analysis of the impact of different amounts of irrigation took into consideration various weather and soil conditions representative of Georgia's ACF Basin. My modelling analyzed the optimal amount of irrigation – the point at which using additional (or “supplemental”) irrigation will not increase the amount of crop produced. My work also analyzed the impact of reducing irrigation below the optimal amount on crop productivity. My analysis is set out in detail in my expert report, a true and accurate copy of which is exhibit FX-792.

6. Before describing the work I performed, I define particular terms and concepts agricultural engineers use to perform research studies similar to the one I performed:

- ***Crop Yield*** is the amount of useful seed generated by a plant and ultimately harvested by the farmer. For example, the “yield” of a corn plant would be how much corn seed the farmer harvested from that plant. Crop yield is generally measured relative to the unit area of the land cultivated – kilograms per hectare or bushels per acre.
- A ***Decision Support System crop model (DSS)*** is a computer program that calculates growth, development, and yield (amount of production) of a particular crop under various circumstances, including weather, soil type, crop management, and plant genetics. As I will describe in greater detail, the Decision Support System for Agrotechnology Transfer (“DSSAT”) is one of the most well-known and widely used DSS models. It uses real world input, is updated continually, and is measured against real world observed data to ensure accuracy.
- ***Irrigation Efficiency*** is a percentage representing the amount of water pumped from a water resource, such as a stream or aquifer, for use in irrigation that

actually makes it into the soil to become available for plant to use. A number of factors influence irrigation application efficiency, including the type of system used, weather conditions, the time of day when water is applied, and cropping conservation measures that are in effect.

- ***Optimal Irrigation*** means the precise amount of water needed to achieve maximum crop yield without using any additional and unnecessary water.
- ***Supplemental Irrigation*** means the use of irrigation water on essentially rainfed crops during times of insufficient rainfall, typically dry or drought conditions, to achieve normal plant growth.
- ***Yield Curve*** means a graphic generated based on the simulated outcomes of DSSAT to show the response of crop yield to changes in the amount of supplemental irrigation applied. The shape of a curve shows that the larger the increase in irrigation, the smaller the increase in crop yield. The shape of the curve also shows that it is possible to significantly reduce the amount of irrigation water used below the optimal amount without causing severe yield losses. An example of this yield response curve is shown in Figure 1 where the horizontal axis of the graph represents the amount of supplemental irrigation applied and the vertical axis represents yield of corn (in kilograms per hectare).

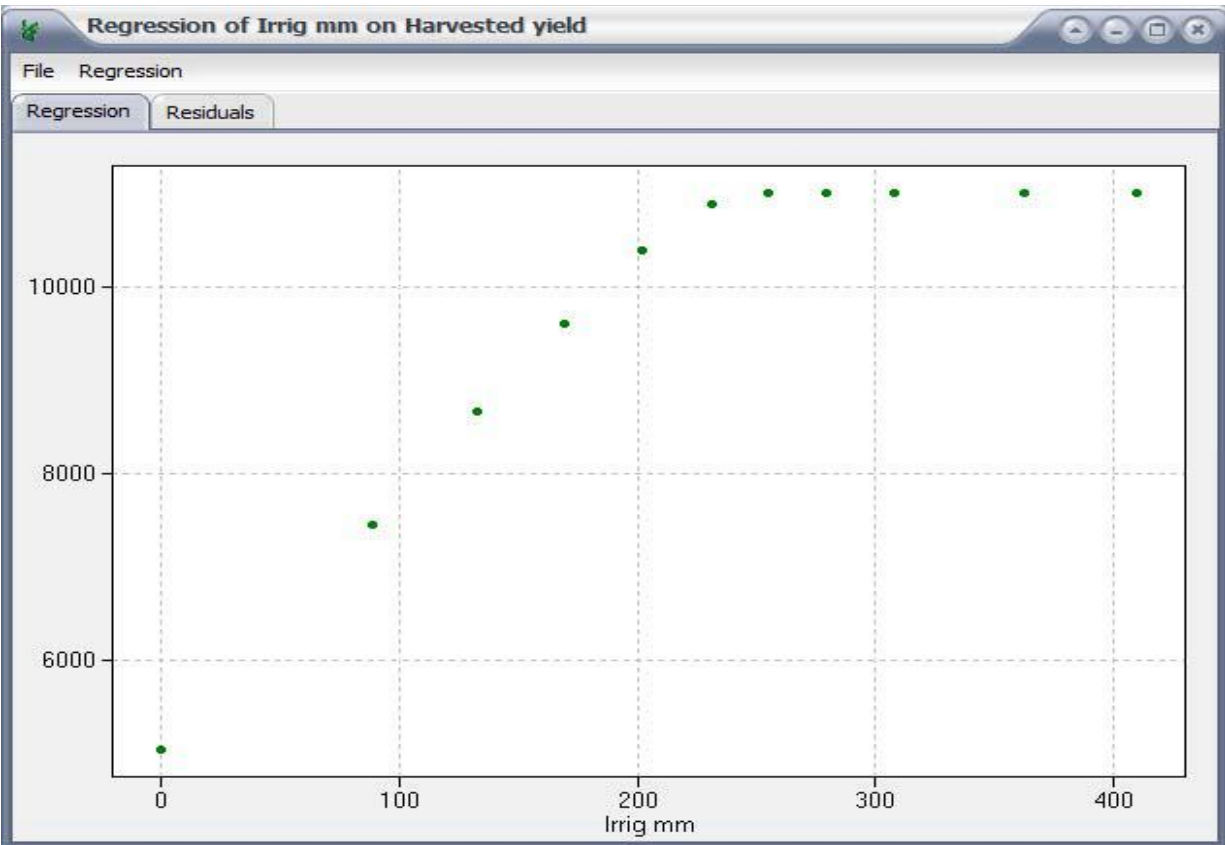


Figure 1. Corn yield response as a function of supplemental irrigation applied. (Hoogenboom Report, FX-792 at 26, Figure 15).

7. I describe the crop model used to conduct this analysis – DSSAT – and the different scenarios, conditions and historical weather data used, and evaluate the results.
8. Based on my modeling and analysis, I reached the following conclusions:
 - **DSSAT is a reliable model for analyzing the relationship between changes in supplemental irrigation and corresponding changes in crop yield for the dominant agronomic crops in Georgia’s ACF Basin.** DSSAT has been used extensively in Georgia and field studies have confirmed its accuracy in Georgia. It is regularly used by other scientists in the field.

- **Dr. Sunding's reliance on outputs from my modeling runs to create a yield curve is well-supported.** Using the DSSAT crop model allows him to accurately gauge the real relationship between crop yields and the amount of irrigation water applied while accounting for variability in local weather and soil conditions.

II. PROFESSIONAL BACKGROUND

9. I am a professor in the University of Florida's Department of Agricultural and Biological Engineering and a Preeminent Scholar at the Institute for Sustainable Food Systems and an Adjunct Professor in the Department of Biological Systems Engineering at Washington State University. From 2010 to 2016 I was the Director of the AgWeatherNet Program at Washington State University and Professor in the Department of Biological Systems Engineering. From 2000 to 2010, I was a Professor in Agrometeorology and Crop Modeling in the Department of Biological and Agricultural Engineering at the University of Georgia and founder and coordinator of the Georgia Automated Environmental Monitoring Network. I received a Ph.D. in 1985 from Auburn University as well as a Master of Science in 1981 and a Bachelor of Science in 1977, both from Wageningen University in the Netherlands. Since completing my Ph.D. in 1985, I have over 30 years of experience as a researcher, university professor and consultant to government agencies at state, federal and international levels. I am a recognized expert in the areas of computer modeling and simulation of agricultural systems, agrometeorology and climatology, the monitoring of weather and environmental variables, and the management of automated weather stations.

10. I am extremely familiar with the DSSAT modeling system as I have been one of the main developers for the past 25 years. I fully understand how the internal computer code functions and the very delicate interactions between weather and soil (environment), genetics,

and crop management, especially irrigation. I frequently organize and facilitate international training workshops on crop modeling and decision support systems, including DSSAT. I have published over 500 scientific papers on DSSAT in scientific refereed journals, books and conferences proceedings.

III. DSSAT BACKGROUND AND HISTORY

11. DSSAT is a decision support system model originally developed during the 1980s under the auspices of a project funded by the U.S. Agency for International Development. Since 1992, the development of DSSAT has been facilitated through the cooperation of various universities, including the University of Florida, the University of Georgia, and the United States Department of Agriculture. DSSAT has been used for many applications ranging from on-farm precision management to regional assessments of the impact of climate variability and climate change. It has been in use for more than 25 years by researchers, educators, consultants, extension agents, growers, and policy and decision makers in over 100 countries worldwide. Today, DSSAT is the most widely-used crop modeling systems in the world and the current release of DSSAT v4.6.1 has been downloaded by more than 3,500 users since September, 2015. DSSAT was used by the State of Georgia to estimate water withdrawal projects for 2020 through 2050 for its “Agricultural Water Demand Forecast.” That forecast was published on the website of the National Environmentally Sound Production Agriculture Laboratory (“NESPAL) at the University of Georgia. A true and accurate depiction of the website for that forecast is JX-38.

12. The DSSAT software includes a number of models specifically designed and calibrated for over 25 different types of crops, including corn, soybean, peanut and cotton. For each crop, DSSAT’s models can evaluate many different scenarios to address a specific question, such as which crop or variety to plant, when to plant the crop, and how much input to apply. To do this, DSSAT uses a complex set of mathematical equations to simulate or “predict” the

development and growth of the plant that is being modeled based on daily time steps from planting until harvest. Specifically, the growth processes that are simulated include the formation of leaves, the occurrence of flowers and other reproductive organs, including seeds and grains, growth of biomass, including leaves, stems, roots and grains and seeds.

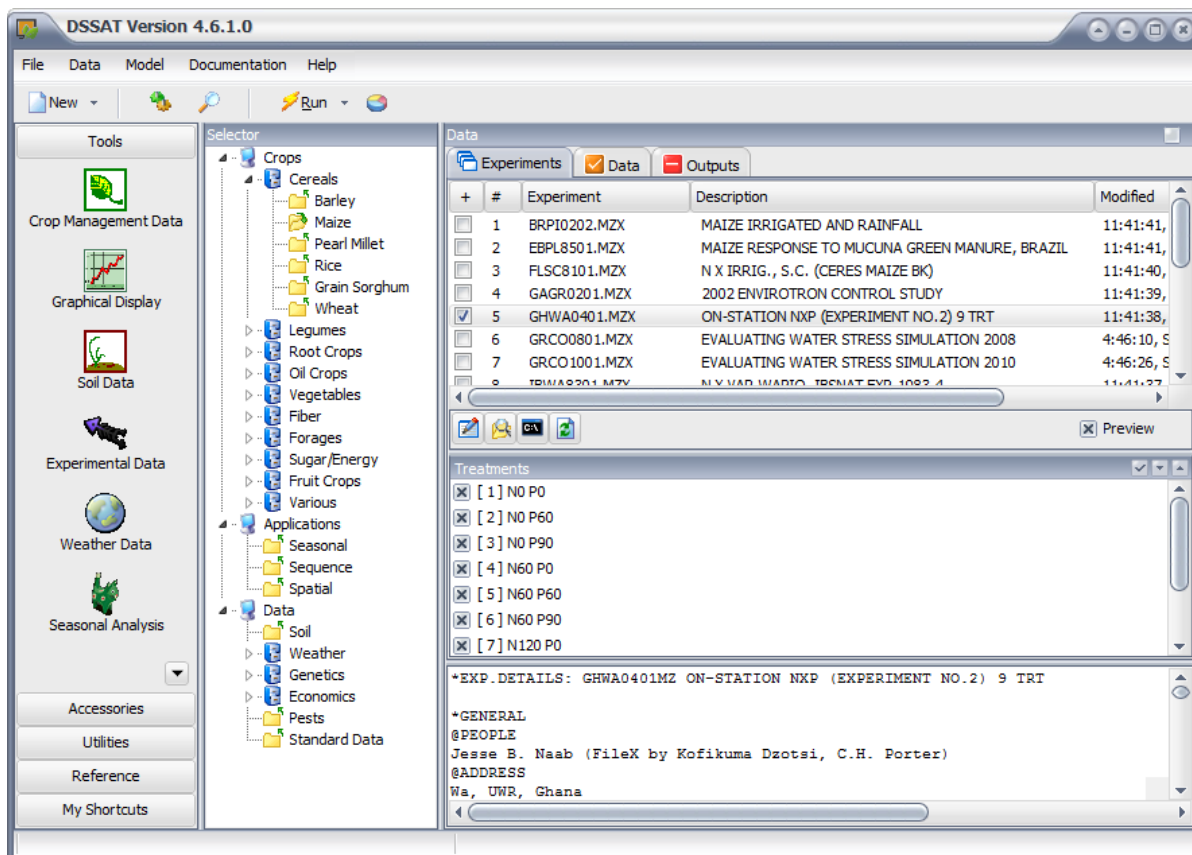


Figure 2 – Screenshot of DSSAT Version 4.6.1.0

13. To accurately account for local conditions over both time and space, DSSAT incorporates a number of data inputs – daily weather conditions, such as maximum and minimum temperature, rainfall and solar radiation, water-holding characteristics of the local soil profile, and crop management practices. The processes that are simulated by DSSAT are based on sound science that has been published hundreds of times in peer-reviewed articles.

14. DSSAT is also continually evaluated against real-world observations to ensure accuracy. Specifically, prior to any application the DSSAT crop model, it is first evaluated, normally with local data from field experiments. During the experiment careful observations and measurements are made for growth and development. Using the weather data, soil water holding characteristics, and other local environmental management conditions, and crop management as input, the simulated data are compared with observed data. In most cases this includes prediction of the flowering and maturity dates, and final yield and biomass. In some cases, other simulated variables are compared with observations, such as soil moisture.

15. Moreover, DSSAT is a reliable model for estimating the relationship between irrigation and yield in Georgia. DSSAT has been used extensively in Georgia, including by the University of Georgia on behalf of the State of Georgia. A careful analysis of that study showed that the simulated results were very similar to the observed water use data.

IV. YIELD CURVE MODELING

16. To analyze the impact of Dr. Sunding's irrigation water conservation measures on crop yields, I used DSSAT to "predict" the impact of different irrigation scenarios (*i.e.* the application of different amounts of water at different times) on the yield of peanut, corn, cotton, and soybean under various weather and soil conditions.

A. Modelling Scenarios Used To Simulate Georgia's ACF Basin

17. In his expert report, Georgia's irrigation efficiency expert, Dr. Suat Irmak, opined that my modeling failed to take into account the variability of weather conditions in the Georgia ACF Basin. This is simply inaccurate.

18. I ran the model using daily local weather data, including air temperature, rainfall and solar radiation for Camilla, Georgia, located in Mitchell County. Mitchell County is a dominant agricultural county within the Flint River Basin and the weather data are representative

of the Flint River Basin as a whole. There is some variability in rainfall amongst Flint River Basin counties, but climatologically rainfall is very similar across the region. My historical weather data covered 67 years to ensure that all weather extremes were captured. When preparing yield responses to rainfall, it is important to use a broad range of historical weather data to capture variability in the weather affecting a particular area, especially wet and dry extremes. The weather data used from the Camilla weather station captures this variability.

19. To capture the variability in soil-water holding capacity of the soils in Georgia’s ACF Basin, my model runs used eight representative soil types comprising the most common soils in Georgia’s ACF Basin. Soil-water holding capacity is the ability of a given type of soil to hold moisture. This is important because more irrigation or rain is needed for soils with low soil-water holding capacity to ensure a plant receives enough water. The opposite is also true.

Rank	Corn		Cotton		Peanut		Soy		Wheat	
	Component	Pct of Total	Component	Pct of Total	Component	Pct of Total	Component	Pct of Total	Component	Pct of Total
1	Tifton	20.6%	Tifton	24.6%	Tifton	23.4%	Tifton	13.8%	Tifton	25.6%
2	Orangeburg	10.6%	Orangeburg	8.8%	Norfolk	10.4%	Greenville	10.4%	Orangeburg	9.5%
3	Norfolk	8.4%	Norfolk	8.7%	Orangeburg	9.5%	Faceville	9.7%	Greenville	9.4%
4	Greenville	8.0%	Lucy	6.2%	Lucy	6.9%	Orangeburg	7.8%	Faceville	7.7%
5	Faceville	7.0%	Greenville	5.5%	Wagram	6.5%	Lucy	7.0%	Norfolk	6.8%
6	Wagram	6.4%	Wagram	5.1%	Greenville	6.0%	Norfolk	6.7%	Red Bay	4.6%
7	Lucy	5.4%	Faceville	4.5%	Faceville	5.2%	Bonneau	6.1%	Lucy	4.4%
8	Troup	4.1%	Troup	4.4%	Troup	5.2%	Blanton	5.6%	Dothan	3.5%
9	Grady	3.9%	Dothan	4.1%	Blanton	3.8%	Dothan	4.7%	Blanton	3.3%
10	Goldsboro	3.9%	Goldsboro	3.5%	Goldsboro	3.2%	Troup	4.6%	Troup	3.0%
11	Red Bay	3.8%	Grady	3.3%	Bonneau	2.9%	Wagram	3.9%	Grady	3.0%
12	Bonneau	3.0%	Blanton	3.1%	Red Bay	2.9%	Fuquay	3.6%	Goldsboro	2.5%
13	Blanton	2.7%	Bonneau	2.4%	Grady	2.8%	Red Bay	3.1%	Wagram	2.5%
14	Dothan	2.3%	Red Bay	2.3%	Dothan	1.8%	Grady	2.0%	Fuquay	1.6%
15	Irvington	1.3%	Fuquay	1.8%	Irvington	1.2%	Lakeland	1.5%	Bonneau	1.6%
16	Ocilla	0.8%	Irvington	1.3%	Fuquay	1.0%	Goldsboro	1.2%	Irvington	1.6%
17	Fuquay	0.7%	Clarendon	1.0%	Clarendon	0.6%	Nankin	1.1%	Nankin	1.2%
18	Americus	0.6%	Nankin	0.7%	Nankin	0.5%	Irvington	0.8%	Carnegie	0.8%
19	Carnegie	0.5%	Ocilla	0.7%	Lakeland	0.5%	Clarendon	0.6%	Lakeland	0.8%
20	Rains	0.5%	Rains	0.6%	Marlboro	0.5%	Cowarts	0.6%	Clarendon	0.7%

Table 1 – The most common soil types in the Georgia ACF Basin

20. Table 1, which was included in my expert report, details eight representative soils in the Coastal Plain of Georgia and the study area, including a (1) a Tifton Loamy Sand, (2) an

Orangeburg Sandy Loam, (3) a Norfolk Loamy Sand, (4) a Greenville Sandy Clay Loam, (5) a Faceville Loamy Sand, (6) a Wagram Sand, (7) a Lucy Sand, and (8) a Troup Sand. Table 1 is a true and accurate representation of information which I received from Dr. Sunding. I understand that Dr. Sunding relied on the USDA SSURGO database for this information. It is the type of information regularly relied upon by experts in my field, and I reviewed and relied upon it in forming my opinions in this case.

21. In terms of irrigation methods, I modeled 10 different irrigation management strategies and one rain-fed strategy in which no supplemental irrigation was applied. To simulate agricultural management practices in Georgia's ACF Basin, I assumed that at planting, the ground was wet to emulate the fact that a farmer probably applied irrigation prior to planting to establish a proper crop. In addition, I conservatively assumed an irrigation efficiency of 85%, which is below the 90-95% irrigation efficiency that the State of Georgia has suggested is possible.

22. For each crop modeled, a total of 5,896 computer experiments/scenarios were simulated – 67 weather years, 8 soil profiles, and 11 water management options. Because DSSAT is in the public domain, the modeling results can be reproduced by anyone who possesses copies of the software and the relevant input files.

B. Modeling Results Were Compared To Observed Field Data

23. Georgia's irrigation efficiency expert, Dr. Suat Irmak, criticized my findings for failure to verify and calibrate my DSSAT modeling with observed field data. This criticism is simply not true. As I have already discussed in detail, DSSAT has been evaluated extensively against observed field data for a whole range of locations in Georgia, including by researchers at the University of Georgia.

24. The model did a nearly perfect job of predicting the observed field data. DSSAT's modeling results for corn, cotton and peanut yield were compared to the observed results of several irrigation studies conducted at the University of Georgia's Stripling Irrigation Park. Detailed studies have also been conducted at the University of Georgia Griffin Campus in rainout shelters to study the impact of different supplemental irrigation amounts on crop yield. These experiments were also modeled and showed the same yield response to supplemental irrigation as was observed,

25. Although the traditional approach to determine the impact of rain and irrigation on crop yield is to conduct field experiments, this approach is simply not viable here. Such experiments are extremely limited in scope since they cannot account for annual weather variability or for differences in local soil characteristics that impact available water for plants. It would take thousands of experiments across decades to capture the interaction between weather and soil conditions and irrigation inputs and the associated crop response. The proper approach is to use a systems analysis approach with a crop simulation model that has been thoroughly tested against observed data to ensure the accuracy of the model. That is the approach I took here.

V. DSSAT MODELING RESULTS

26. For my work in support of Dr. Sunding, I evaluated the impact of different amounts of irrigation water application to both wet and dry soils, taking into consideration all the factors I've already discussed – soil type, weather, and different management practices. The modeling evaluation created yield curves for each of the four crops studied. These yield curves show how the crop's yield responds to the application of different amounts of irrigation under a variety of different circumstances. Specifically, the yield curves show the threshold at which additional irrigation does not increase yield – the optimal amount of irrigation. Irrigation above

this threshold is therefore excessive. The yield curves also show the impact of reducing irrigation water application below the optimal amount. By modeling reductions in the amount of irrigation water used, we can evaluate the associated impact on crop yields with these different reduced irrigation scenarios. This allows us to determine how much irrigation can be reduced, and thus how much water can be conserved, without causing severe reductions in crop yield.

27. The results of my DSSAT crop yield simulation modeling are described in detail in my expert report. In short, and as expected, the modeling showed that yield of soybean, peanut, corn, and cotton are highly responsive to supplemental irrigation. It is important to note that my work was not trying to predict crop yield in absolute terms but, rather, to show how yield would vary based on different irrigation management regimes.

VI. SUMMARY

28. DSSAT crop simulation models are an excellent tool for understanding the dynamics between crop growth, development and yield, local soil and weather conditions and crop management. Further, Dr. Sunding's reliance on outputs from my DSSAT modeling runs to create a yield curve is well-supported. His use of the modeling approach accurately allows him to determine the real relationship between a crop's yield response and different crop management scenarios, including irrigation, and local weather and soil conditions.

29. In my testimony, I referenced two documents. True and accurate copies of those documents have been submitted into evidence, and I describe the documents and my familiarity with each of them below:

- a. FX-792 – Expert Report of Dr. Gerrit Hoogenboom: This is a true and accurate copy of the expert report I produced for the State of Florida in this litigation, which I prepared using generally scientifically accepted principles and methodology.

- b. JX-38 – James E. Hook, et al., Agricultural Irrigation Water Demand Forecast (2009): This is a true and accurate copy of the Agricultural Irrigation Water Demand Forecast that the State of Georgia used to estimate water withdrawal projects for 2020 through 2050. It is the kind of analysis and report regularly relied upon by experts in my field, and I reviewed and relied upon it in forming my opinions in this case.