A GIS Analysis of the Relationship between Sinkholes, Dry-We Groundwater Pumping for Frost-Freeze Protection of Winter S Production in Florida

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Abstract

Florida is riddled with sinkholes due to its karst topography. Sometimes these sinkholes can cause extensive damage suggested that agricultural practices, such as sprinkler irrigation methods used to protect crops, can increase the dev temperatures drop below freezing, causing groundwater levels to drop quickly during groundwater pumping. In the stra Florida, the effects have caused water shortages resulting in dry- wells and ground subsidence through the developme and repair. In this study, we look at how frost-freeze events have affected West Central Florida over the past 25 years two cold-years (with severe frost-freeze events) and a warm year (no frost-freeze events). We analyzed the spatial a farming freeze protection practices and the development of sinkholes/dry well complaints, and assessed the economic management perspective by evaluating the cost of repairing and drilling new wells and how these compared with using found that the spatial distribution of sinkholes was non-random during both frost-freeze events. A strong correlation be extraction and minimum temperatures was found. Furthermore as temperatures fall below 41°F and water levels decr sinkholes increase greatly (N >10). At this time alternative protection methods such as freeze-cloth are cost prohibitive conclusion, the findings from this study are applicable in other agricultural areas and can be used to develop compreh where the abstraction of large quantities of water occur.

Figures

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Introduction

The US is the world's largest producer of strawberries [1]. Although, California is the largest producer of strawberries winter strawberries due to the mild winter climate [1]. The main growing area in Florida is in the Dover/Plant City Area approximately 5800 acres are harvested annually [2].

In Florida, strawberries are planted in November and peak during March (see [3] for timeline). Although winter temper 74.6°F [4], strawberries and other horticultural crops are sometimes exposed to frost-freeze events when temperatur time (see [5]). During these conditions, farmers use either active or passive methods to protect fruit crops [6]. Active machines, sprinklers, surface irrigation, foam insulation, or a combination of each [7]. Passive methods can include sit management, plant covers, irrigation, and soil covers [8]. In Florida, farmers use sprinkler irrigation, soil banking and/c during frost-freeze events. Of these methods, the sprinkler irrigation method is the most widely used, not only in Floric damaged by frost-freeze events (e.g. Canada [10]; Louisiana [11]), because it is relatively easy to administer and cc Essentially, water is sprayed onto the plants, forming a layer of ice on the plant or fruit crop that protects the plants fr disadvantage is large quantities of water are pumped from underground aquifers in a relatively short period of time, w shortages and sinkholes [13]–[15]. Since 1985, population and farm acreage have increased in this area resulting in hi home-owners, which has the potential to amplify water shortage issues and accelerate sinkhole development [16].

Florida is mainly composed of limestone and is prone to sinkhole development through dissolution by water [17]. Since sinkholes reported to the Florida Geological Survey (FGS) with the greatest number occurring in 1980's and 2010 [18] reported sinkholes has declined over recent years, as compared to the 1980's when reporting was highest due to high drought conditions [18], numbers increased dramatically during the winter of 2009–2010 (*N* = 179 for 2 months). Sinkl population, but cause extensive damage [16], [19]–[22]. For example in Florida, during January 1977, groundwater wa Floridan Aquifer to protect strawberry crops resulting in a 9.51 foot reduction of the water level and an increase in the were large enough to cause damage to property and infrastructure. In 1981 in Orange County, FL, a massive sinkhole destroyed multiple homes, businesses and swimming pools [20], [24], [25]. In 1985, 27 sinkholes, between 2 to 75 ft freeze in Hillsborough County, Florida during January when well water levels dropped 17 ft [14]. In 1994, a 15-story si gypsum stack pile (toxic industrial waste) at the IMC-Agrico's New Wales Plant in Polk County, FL [17], [26]. More rec was discovered during a routine inspection of an inactive phosphogypsum disposal stack which measured 160 feet in surface [27]. Recently, in 2010, during a two month period (January and February) more than 140 sinkholes occurred County, FL, where water was used to protect strawberries [28]. The damage during this event resulted in the destruct of nearly $1 million [29].

Although studies have investigated the linkage between sinkhole development and ground water pumping in Florida, th farmers has only been analyzed for specific years. For example, in 1973, Watson and Company showed that while pu developed in close proximity to where the pumping occurred both during and after the testing exercise [30]. Using this suggested that the development of sinkholes, as a result of a freeze event when temperatures dropped to 25°F on Ja 22 sinkholes when water was extracted for the protection of strawberries. Bengtsson [14] further examined changes i farms, and the development of sinkholes during the frost-freeze event of 1985. His findings suggest that there is stron intense irrigation to protect crops. A limitation of the aforementioned study is that only a single event was examined ar water level during the 1985 frost-freeze event.

In this study, we look at how frost-freeze events have affected West Central Florida over the past 25 years with detai (with severe frost-freeze events) and a warm year (no frost-freeze events). Geographic Information Systems (GIS) w relationship of frost-freeze events to the development of sinkholes/dry well complaints in the strawberry farming regio through the use of sprinklers can result in extensive damage through the development of sinkholes and dry-wells. We frost/freeze events from a water management perspective by evaluating the costs associated with repairing and drillin non-water based crop-protection methods.

Methods

To analyze the link between ground water pumping during frost-freeze events and sinkhole development, the occurren investigated. Three specific years were selected to analyze. These include two years with severe-frost-freeze (1985, events (2007).

Damage to tender crops such as strawberries occur when temperatures range between 32°F (0°C) and 22°F (−1°C) frost-freeze event was defined to occur when temperatures fall to 32°F (0°C) and below. Minimum daily temperatures were obtained from NOAA [31]. Daily minimum temperature data between December 1 and January 31st on a yearly from NOAA's 11 stations in the Tampa Bay Area [31]. Although stations were within and around the Dover/Plant City s temperature station data was used as it had the most consistently reported dataset for the 25 year timeframe. Howev stations were used when analyzing sinkhole occurrence during 1985, 2007 and 2010.

Years absent of frost-freeze events were identified by averaging daily minimum temperatures for each winter (Decem winter was considered to occur when no temperatures fell below 32°F and the mean winter average was above the 2 2007 satisfied the aforementioned criteria and was therefore selected to represent a warm year for this analysis. The include the recent winter of 2010 during which some of the coldest temperatures were experienced in 25 years and 19 fields and water extraction has previously been analyzed for 1985 by Bengtsson [14], it was included in this study as a

During a frost-freeze event, strawberry farmers pump large volumes of water to protect their crops from damage. To method, the occurrence of sinkholes and dry well complaints with minimum temperatures and water levels were analyz Sinkhole data is collected by the Florida Department of Environmental Protection (FDEP) - Florida Geological Survey Florida's natural resources and was obtained from the Florida Geological Survey [18]. This dataset contains the locati subsidence incidents and the date each incident was reported. The reports made to the FGS do not provide the cause verified or field checked by a professional geologist. Though the database has true sinkholes, the majority are subside all subsidence incidents have been identified as "sinkholes". Although, this dataset may have limitations associated wit has previously been used in other analyses (see [17], [32]) and is the most comprehensive dataset available at this tir

Population data was obtained by census block group data for four decades (1980, 1990, 2000, and 2010) for areas in Geographic Data Library (http://www.fgdl.org/metadataexplorer/explorer.jsp). Locations of strawberry fields were obt location of strawberry fields in the Plant City/Dover Area for 1984, 2007 and 2010. Although, the frost-freeze event fo information used in this study was only available for 1984 and was therefore used to represent the strawberry field loc were acquired from Tampa Bay Waters (TBW) Mitigation Database. Each dry well complaint record is geo-referenced associated costs. SWFWMD also recorded 688 dry well complaints, however the data was provided as a total numbe basis level, which was needed for the temporal analysis, therefore it was only used in the spatial analysis portion of th

Two types of water data were used in this study. Daily water levels (in feet) were obtained from Tampa Bay Water fo study area. Three monitoring sites contained sufficient data over the 25 year period include: ROMP DV-1 SUWANNEE BD-18FL. Data for an 8-week period (December 1st through January 31st) were extracted from these sites for each exception of 1991. For unknown reasons, these monitoring sites did not capture data for 1991. This data was used to water levels, number of sinkholes, and drywell complaints. In addition, groundwater use permit volumes for crop prote [33]. These attributes include, latitude, longitude and daily maximum allowable volume of water that farm is permitted day (gpd)).

Analysis

To analyze the spatial distribution of sinkholes/dry-well complaints and their proximity to strawberry fields in the Plant C tools available in ArcGIS 10 (ESRI, Inc., Redlands, CA) were utilized. Point pattern analysis methods that have succe (see [34] for overview) in urban areas (eg. [35], [36])), forest environments [37]) and the spatial distribution of 911 cal useful in highlighting key areas where certain types of crime were clustered (e.g. Kernel Density Estimation (KDE), Av estimates were used to create surfaces for sinkholes and dry well complaints to easily identify areas where a large nu study area. The NNI method was used to identify clustering of sinkholes and drywell complaints by examining conform (IRP) by calculating a ratio (R) of the observed mean nearest neighbor distance to the expected mean nearest neighb complaints. This method calculates a nearest neighbor index based on the average distance from each point feature t Clustering occurs when values of R<1 [40].

Distance to strawberry farms was calculated to the polygon centroid from each sinkhole and dry-well complaint point. sinkholes, dry well complaints, minimum temperature and change in water level were tested using Spearman's rank co

Economic Assessment

In the Tampa Bay Area, a major push is being made to create incentives/cost sharing programs to encourage farmers 2010, SWFWMD implemented a Facilitating Agricultural Resource Management Systems (FARMS) to help cost share farmers in Dover/Plant City [41]. SWFWMD covers 75% of the cost farmers will incur for purchasing freeze-cloth to co the economic impact of frost-freeze events in the areas surrounding the strawberry farms, we investigated the cost as installation of new wells in comparison to using freeze-cloth (a non-water based protection method).

A cost analysis was completed by calculating the total cost of the freeze-cloth that would have been needed during 20 the TBW dry well complaint cost database. To do this we calculated the total cost of freeze-cloth that would be requir of 2010 the cost of the freeze-cloth per acre was $2,400, which includes average labor costs of $300 per acre [42]. T estimated from the strawberry farm dataset, previously described, and used to calculate the total cost of the freeze-c above. The total cost associated with reported dry well complaints were extracted from the TBW dry well complaint c between December 1st and January 31st for 2007 and 2010 and the totals calculated. Data was not available for 1985

Results

Since 1985, in the Dover/Plant City study area, there has been considerable growth in both population and strawberry 30 years from 91,000 to 234,000 people with the greatest increase occurring between 1980 and 1990 (84% increase this growth, the acreage of strawberry fields has also increased by 389% from approximately 2,800 acres to 11,000 a

Spatial and Temporal Analysis of Sinkholes and Dry Well Complaints

Between 1985 and 2010 the largest number of sinkholes were recorded during the winter of 2010 (N = 131) with the s 1985 (N = 30) (Figure 1A). Two additional years (1990 and 2003) also had sinkhole incidences, but these were low (N years. Since 1990, dry-well complaints have been recorded during most years with the highest number of complaints

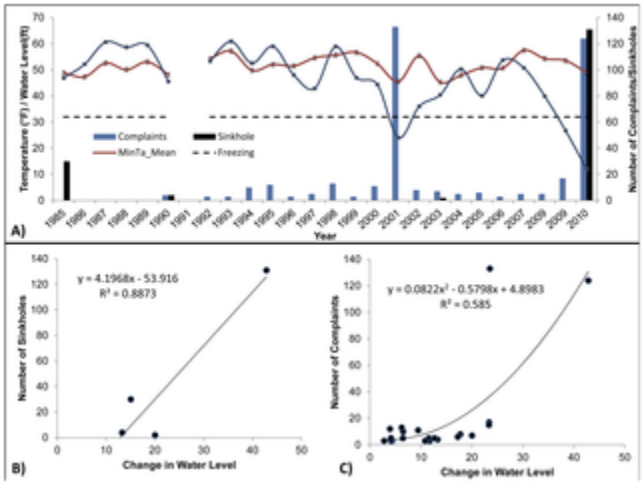

Figure 1. Graph illustrating the occurrence of sinkholes and dry-well complaints between 1985 and 2010 ir (°F), water level (ft) and changes in water level.
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Minimum temperatures fluctuated between 50°F and 55°F with the coldest temperatures occurring during 1986, 2001,

temperatures were below 50°F, 12°F below the average for this time of year (Figure 1). Water levels also varied durir levels are close to 60 ft and dropping as low as 14 ft during 2010. Water levels dropped for 3 consecutive years reacl highest number of recorded dry well complaints). Prior to 2010, water levels also exhibited a similar pattern to 2001, v were low for 4 consecutive years. Our initial analysis of sinkholes and dry well complaints in relation to minimum temp from 1985 to 2010 clearly show that when water levels fall below 27 feet the number of sinkholes and dry well compla relationship was found between number of sinkholes and dry well complaints and changes in water level (Figure 1A ar

The spatial (Figure 2) and temporal (Figure 3) distribution of sinkholes and dry well complaints in the strawberry grow three individual years that include 1985, 2007 and 2010. For this study, the majority of sinkholes and dry well complair to the strawberry farms. The majority of the sinkholes occurred within a ¼ mile range of these farms (63% (1985), 45 up to ½ mile from strawberry fields (0 (1985), 72% (2010)). A similar pattern was observed with dry well complaints v occurring within ½ mile of strawberry fields and the majority occurring within a ¼ mile (40% in 2007 and 41% in 2010) 1, 2006–January 31, 2007) 5 dry well complaints were recorded (Figure 3A) with an apparent random distribution (*NN* found between dry well complaints and minimum temperature ($n = 45$, $r = 0.110$, $P<0.05$) and change in water level (r

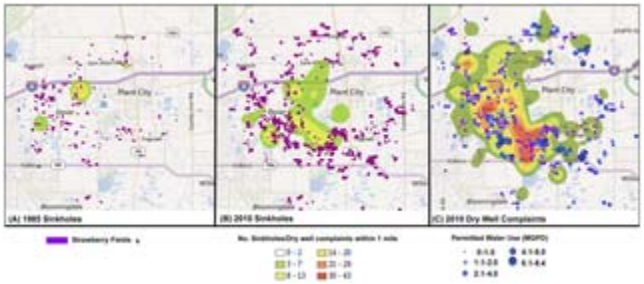

Figure 2. Maps illustrating the density of (A) sinkholes in 1985, (B) sinkholes in 2010 and (C) dry well comp of strawberry farms and groundwater use permits rates (MGPD).
doi:10.1371/journal.pone.0053832.g002

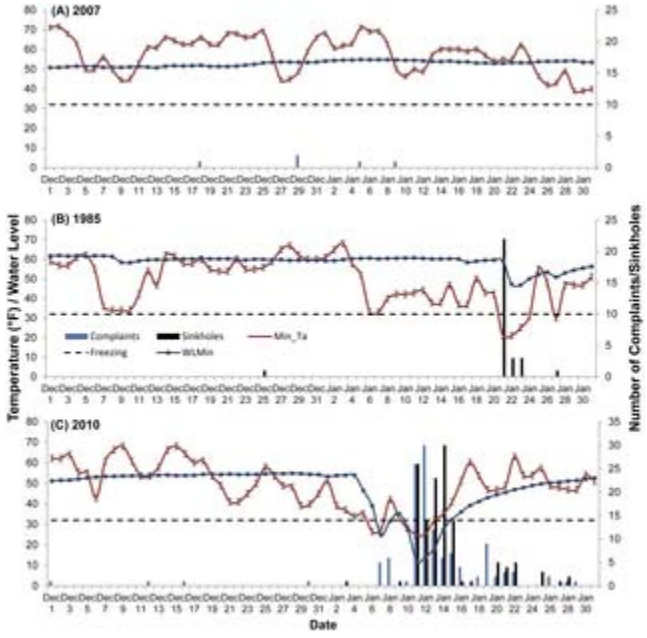

Figure 3. Summary of water level (+/− SE) (WLMin), minimum temperature (°F)(+/− SE)(Min_Ta), and the nu complaints recorded during December 1st through to January 31st for (A) 2007, (B) 1985 and (C) 2010.

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Clustering of spatial and temporal occurrence of sinkholes was found during frost-freeze events in 1985 and 2010, an
Between December 1st, 1984 and January 30, 1985 the incidence of sinkhole and dry well complaints are illustrated i
sinkholes were clustered (*NNI = 0.11, P<0.01*) (Table 1). In 1985 temperatures fell below freezing for a total of 4 day
levels dropped 20% (59 ft to 47 ft). A total of 22 sinkholes were reported with the majority being reported over 4 day
between the number of sinkholes and a change in water level (*n = 5, r = 0.276, P<0.05*).

Year	Number	Observed Mean Distance (meters)	Expected Mean Distance (meters)	Nearest Neighbor Index	Z-Score	P-value	Clustering
Sinkholes							
1985	30	253.88	2362.91	0.11	−9.35	0	Clustered
2010	131	391.75	1126.47	0.03	−14.34	0	Clustered
Dry Well Complaints							
2007	5	4730.33	5787.92	0.82	−0.78	0.43	Random
2010	806	205.42	1490.73	0.14	−47	0	Clustered

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Table 1. Nearest Neighbor analysis test statistics for sinkholes and dry-well complaints during 1985, 2007
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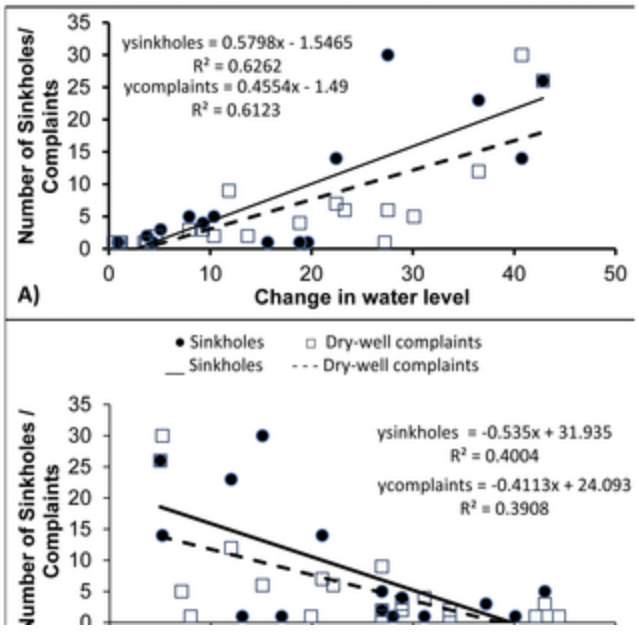
In the winter of 2010 (December 1, 2009–January 30, 2010) the spatial and temporal distribution of sinkhole and dry
and 3C. Similar to 1985, spatial clustering of sinkholes (*NNI = 0.034, P<0.01*) and dry well complaints (*NNI = 0.14, P*
highest density of dry well complaints and sinkholes were found in close proximity to larger strawberry fields (Figure 2

Temperatures fell below freezing twice for a total of 7 days reaching a low of 25°F (Figure 3C). During these two day
ft) with 11 dry well complaints reported. Following the second cold spell, when temperatures remained low for 5 cons
total of 130 sinkholes were reported with the majority being reported over 20 days after the end of the cold temperatu
well complaints were reported to Tampa Bay Water and 688 were reported to SWFWMD for a combined total of 806

A strong positive correlation was found between the occurrence of dry well complaints (*n = 22, r = 0.783, P>0.05*)/sir
in water level (Figure 4A) and a strong negative correlation between sinkholes (*n = 15, r = 0.632, P>0.05*)/dry well co
minimum temperature (Figure 4B). Furthermore, when temperatures fall below 41°F and water levels fall more than 2
(*N* >10) (Figure 4C).



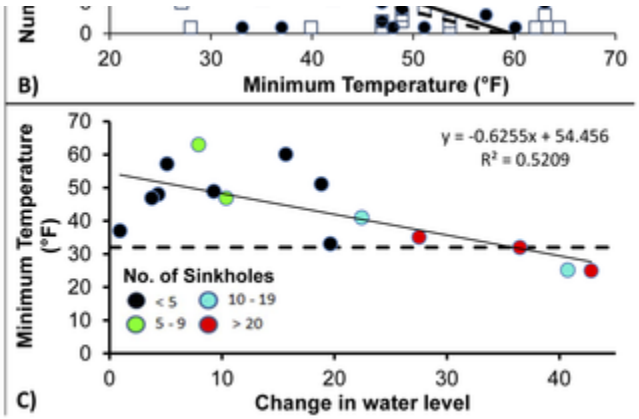


Figure 4. Graph illustrating the relationship between dry-well complaints and sinkholes during 2010 in rela minimum temperature (°F) and (C) the relationship between minimum temperature and changes in water le
doi:10.1371/journal.pone.0053832.g004

Economic Impact

For 2007, the total cost associated for dry well complaints was $12,859 (*N* = 5) and $472,951 (*N* = 124) during 2010 freeze-cloth to protect strawberry plants was estimated to be $16.5 million for a total of 6,900 acres of strawberry fie subsided, the estimated cost to the farmers would have been $4.1 million, while the total estimated cost to SWFWMD

Discussion

The occurrence of sinkholes as a result of groundwater pumping is not limited to Florida. Subsidence has also been d of water are removed for agricultural and industrial use in other parts of USA [43], [44], particularly California (e.g. Sa [46]), and regions of China (e.g. Su-Xi-Chang [47]). Although we only investigated how water-based crop protection m strawberry farms in this study, there are a number of other agricultural systems in Florida that also use this method to vegetable, vegetation, nursery and ornamental farms and tropical fish farms [9], [48], [49]. Of these, strawberries use (citrus) to 13,500 (Ferns) [48]. Many farmers use the Florida Automated Weather Network (FAWN) Data, an internet schedule irrigation times [48]. Even efficient tools such as FAWN, which are useful in reducing water depletion, can on withdrawal rates that can be damaging and cause dry wells and development of sinkholes [50]. Since Florida is mainly sinkhole and dry well complaints will continue to develop in agricultural areas where extreme pumping of water occurs determine if the pattern exhibited in strawberry growing regions is also likely to occur in other agronomic cropping are

In this study, we found that the majority of the sinkhole and dry well complaints occurred within 1/4 mile of strawberry between minimum temperature and change in water level but also between the occurrence of sinkholes and dry well c the 2010 frost-freeze event. The results from this study further support the findings of previous studies [14], [23], [30 between the aforementioned studies and this study is that they each analyzed a single event for a single year. This stu compared those to a non-frost-freeze year as well as examined the incidence of sinkholes and dry well complaints ove able to show that the location of dry well complaints as well as location of permits where more than 1 MGPD of wate proximity to strawberry farms. This study benefited from improved data collection since 1985 as well as the use of GI Furthermore, GIS allowed for the visualization, examination and modeling of data to assist in understanding the occurr relation to strawberry farms, water level/change and minimum temperatures.

Throughout the time scale of this study, Florida has experienced several droughts that include: early 1980's, 1989–19 had considerable impact on water levels in this area, resulting in the need for additional water supplies. Until 2002, the groundwater sources after which alternative sources, such as desalinated water and surface water, have been used [complaints were recorded. There is a strong possibility that these may be as a result of the drought conditions and re

After the January 2010 frost-freeze event, SWFWMD adopted a comprehensive management plan to address future f sinkholes, potentially caused by irrigation [13]. The management plan includes several recommendations, the relevant from this study and include; (i) establishment of critical minimum water level (ii) install automatic meter reading devices recording; (iv) expand data collection network for freeze events; and (v) increase incentives for using alternative frost-

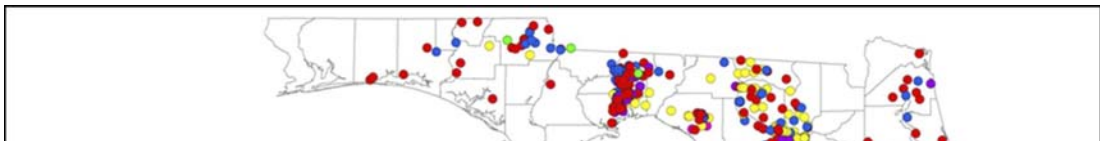
i. Establishment of critical minimum water level: The research findings from this study indicate that during the dropped below 20 ft the number of sinkholes increased substantially. Therefore, establishing a critical minir the drastic water level drops to the aquifer as seen during 2010 when water levels dropped approximately specific rules addressing the Dover/Plant City WUCA (Water Use Caution Area), MAL (Minimum Aquifer Le Protection Zone) have been implemented by SWFWMD (see [49] details).
ii. Install automatic meter reading devices; Farmers are currently permitted to extract a certain amount of wa report accurate daily production quantities. Automatic meter reading devices will assist in identifying fields v than permitted (Figure 2C). The data recorded from these meters can help improve our understanding of tl water levels that have been set (see (i)) particularly during years when water levels are below normal.
iii. Ensure more consistent and reliable data recording protocols to track reported sinkhole and dry well comp well complaints were omitted from the temporal analysis because the dates of when they occurred were n attribute field to the storage database to track the date a sinkhole or dry well complaint incident is reported analysis of events.
iv. Expand the data collection network for freeze events to include additional temperature and water level mor monitoring. Consistent and reliable data recording was a problem throughout this study. Initial analysis of th years the most consistent records for temperature data was at the Tampa International Airport location, 23 closer to the strawberry farms only contained data for the past 16 years Since a strong correlation was fo dry well complaints with changes in water level (and minimum temperature and changes in water levels) im enhance forecasting capabilities and future recommendations. The installation of a number of additional mo recently been completed to improve the understanding of freeze protection drawdown characteristics and u as illustrated by [49]. In addition, these data can be used to predict density of sinkholes as shown by Doct sinkhole risk [54]; and map irrigation requirements [55].
v. Finally, a key recommendation from the management plan was to increase incentives for using alternative f alleviate the use of excessive water usage in the Dover/Plant City Area. One alternative that was examined analysis showed that the current cost of implementing this method is prohibitive when compared with the c and cooperation systems, such as FARMS, could be key in reducing groundwater pumping, to make this a need to be reduced substantially. However, an advantage of utilizing this method is that the cloth can be re- SWFWMD would both be faced with a high initial cost which would be substantially reduced over time. Futu labor to place the cloth over the crops.

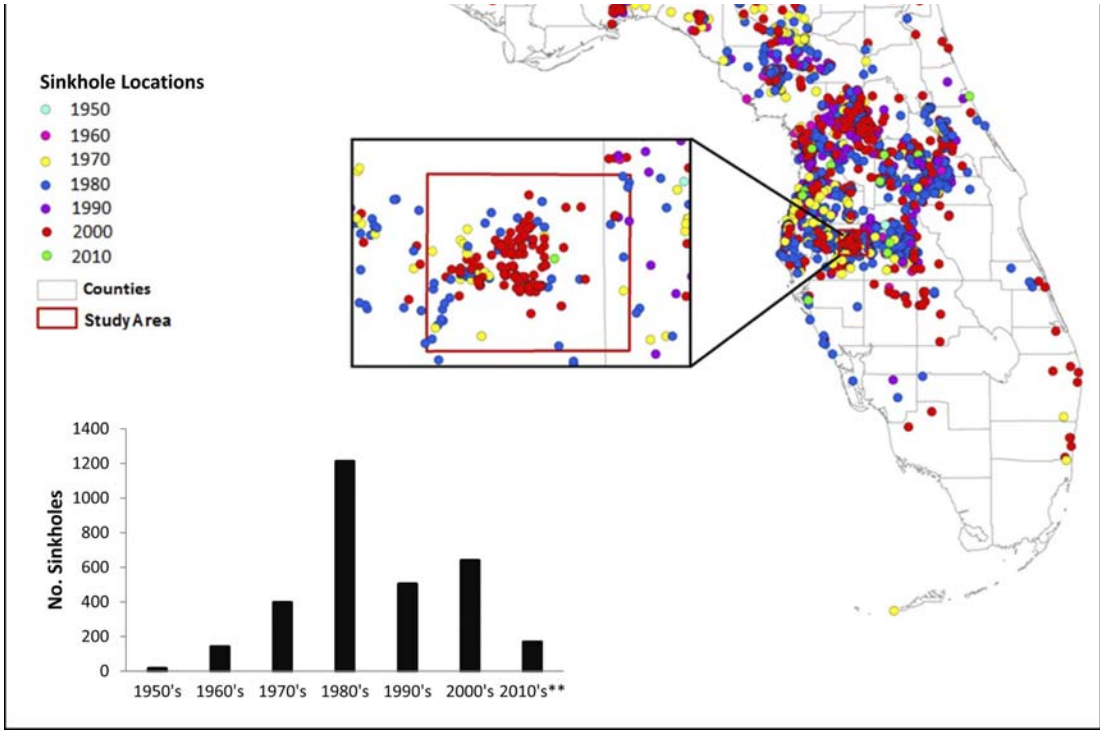
For this study, we only analyzed the cost of repairing dry well complaints. The cost of repairing damages caused by s analyzing the cost incurred by the water authorities. However, additional costs of damages caused by the sinkholes w (e.g. $7.6 million [56]) and represented in this analysis.

In conclusion, frost-freeze events will continue to impact the environment in Florida if water-based methods are used t minimum temperature and water level/change in water level was found during the 2010 frost-freeze event. The occurr minimum temperatures fall below 41°F and water levels drop by more than 20 ft. In addition, prolonged droughts are l complaints and sinkholes. Years where base water levels are already lower than normal, combined with cold tempera numerous sinkholes and dry well complaints as recorded during the winter of 2010/2011.

Supporting Information

Figure_S1.tif





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Total number of sinkholes reported to the Geological Survey in Florida by decade between 1950 and 2010 (FGS, 2011).

Figure S1.
Total number of sinkholes reported to the Geological Survey in Florida by decade between 1950 and 2010 (FG
doi:10.1371/journal.pone.0053832.s001
(TIF)

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improve this manuscript.

Author Contributions

Conceived and designed the experiments: MA JIB. Performed the experiments: JIB MA. Analyzed the data: JIB MA. \

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