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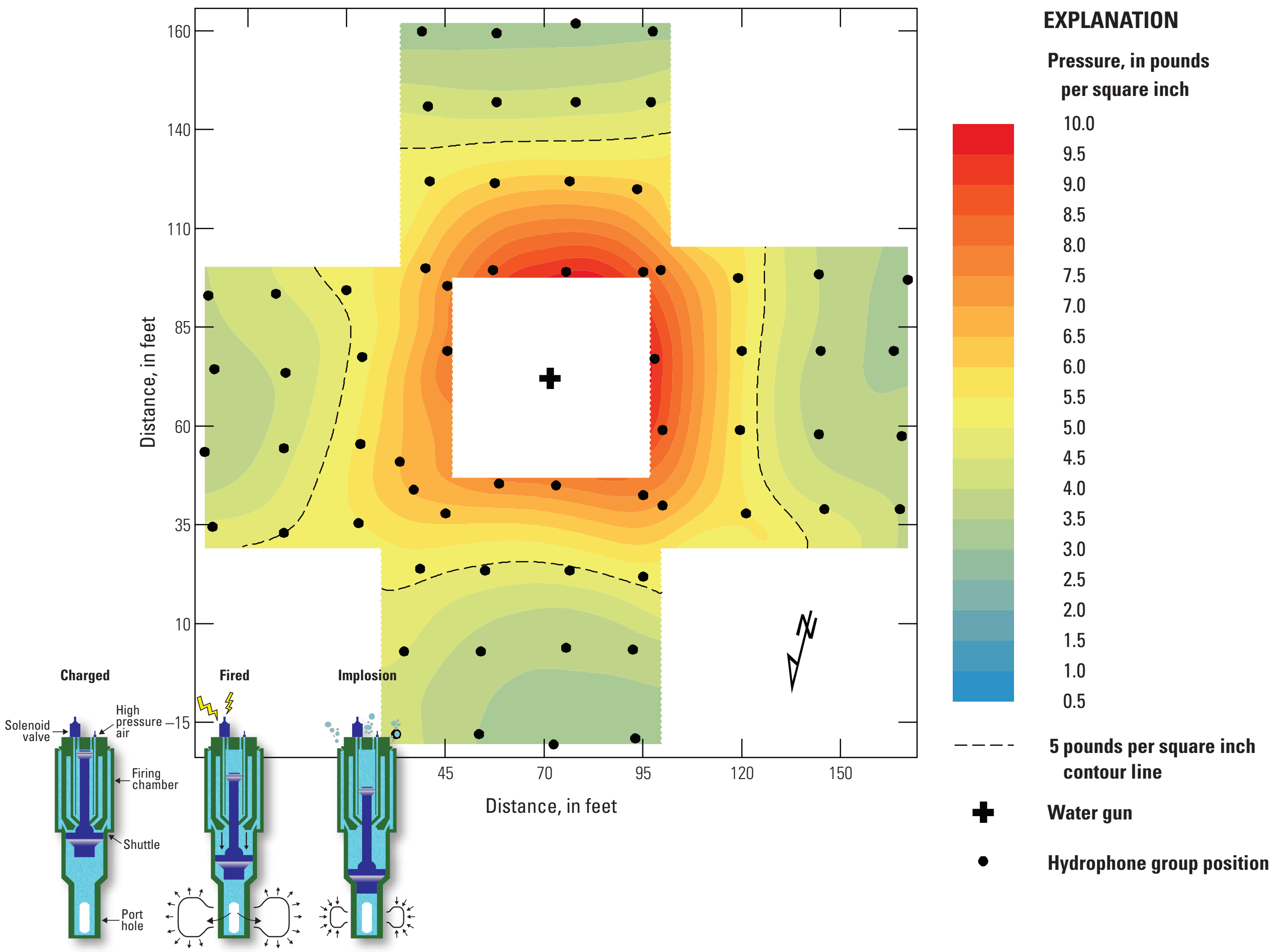
Geophysical Investigation of the Pressure Field Produced by Water Guns at a Pond Site in La Crosse, Wisconsin



Open-File Report 2015–1130

U.S. Department of the Interior
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Cover images. Water gun firing schematic (foreground, diagram redrafted from Layhee and others, 2013), and pressure map from 80-cubic-inch water gun fired at 2,000 pounds-per-square-inch, measurements at a depth of 3.5 feet (background).

Geophysical Investigation of the Pressure Field Produced by Water Guns at a Pond Site in La Crosse, Wisconsin

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U.S. Department of the Interior
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U.S. Geological Survey
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Contents

Figures

Figures—Continued

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
	Area	
acre	0.4047	hectare (ha)
	Volume	
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

Geophysical Investigation of the Pressure Field Produced by Water Guns at a Pond Site in La Crosse, Wisconsin

By Ryan F. Adams and William S. Morrow

Abstract

Three different geophysical sensor types were used to characterize the underwater pressure waves generated by the underwater firing of a seismic water gun and their suitability for establishing a pressure barrier to potentially direct or prevent the movement of the Asian carps. The sensors used to collect the seismic information were blast rated hydrophones and underwater blast sensors. Specific location information for the water guns and the sensors was obtained using either laser rangefinders or differentially corrected global positioning systems (GPS).

Two separate studies are discussed in this report. The two studies were completed during September 2012 and July 2013. Both of these studies took place in an earthen testing pond on the campus of Upper Midwest Environmental Sciences Center (UMESC) in La Crosse, Wisconsin.

Previous studies had identified 5 pounds per square inch (lb/in^2) as a target value for the successful operation of a water gun barrier. The September 2012 study evaluated the performance of 1-cubic-inch (in^3) and 80-in^3 water guns. Data from the 1-in^3 gun showed that it produces a very planar wave with limited effect on the depths above and below its gun ports. The 1-in^3 gun did not produce the 5-lb/in^2 target pressure at a sufficient distance to be considered effective. The 80-in^3 gun produced a bowl-shaped pressure field with the 5-lb/in^2 target radius at the surface extending to 45 feet.

The July 2013 study consisted of three scenarios: fish behavior, single gun assessment, and experimental barrier evaluation. The fish behavior scenario simulated the pond conditions from previous studies. Two 80-in^3 water guns were fired in the south end of the testing pond. Pressures essentially doubled from the testing of the single 80-in^3 water gun. The single gun assessment scenario sought to replicate the setup of the 80-in^3 scenario in September 2012, but with additional sensors to better define the pressure field. The 5-lb/in^2 target pressure field continued to show a radius ranging from 40 to 45 feet, dependent on the pressure of the input air. The final scenario, the experimental barrier evaluation, showed that a two-dimensional continuous plane of 5 lb/in^2 can be created between two 80-in^3 water guns to a separation of 99 feet and a depth of 6.5 feet with 1,500 lb/in^2 of input air.

Introduction

Two species of invasive Asian carps (bighead carps *Hypophthalmichthys nobilis* and silver carps *Hypophthalmichthys molitrix*) are threatening to move into the Great Lakes from the Mississippi River Basin. The primary connection between the Mississippi River and Great Lakes Basins is through the Chicago Area Waterway System (CAWS). The U.S. Geological Survey (USGS) is studying the potential effectiveness of using water guns to produce a pressure barrier to direct or prevent the movement of the Asian carps.

Water guns use large amounts of high-pressure air to eject a rated volume of water at a rapid rate. The ejection of the water creates a vacuum which is rapidly filled by the collapse of water back into the empty space. When the water returns back into this empty space, a pressure wave is created.

Various studies have investigated the effects of water guns on fish and other marine life. Responses of several fish species to water guns indicate that underwater pressure waves may alter fish behavior (Lokkeborg and others, 2012). Other studies report results that range from small changes in fish behavior (Turnpenny and Nedwell, 1994; Wardle and others, 2001) to mortality (Gross and others, 2013).

Fish behavior data collected as a separate investigation during these pond experiments indicated that a pressure near 4 pounds per square inch (lb/in^2) was sufficient to affect the movement of Asian carps (Romine and others, 2015). Additionally, 5 lb/in^2 above the static water pressure was given as the pressure limit in the use of water guns near sensitive structures (Fred Joers, U.S. Army Corps of Engineers, oral commun., 2013). In recognition of both of these values, 5 lb/in^2 was used as a benchmark for the evaluation of water gun barriers.

The measurement of the physical magnitude and extent of pressure output of water gun(s) used in an earthen test pond in September 2012 and July 2013 is the focus of this report. The magnitude, direction, and impacts of the pressure output on Asian carp, native species, structures, and other recipients is a larger USGS goal. This project was funded through the Great Lakes Restoration Initiative as administered by the U.S. Environmental Protection Agency.

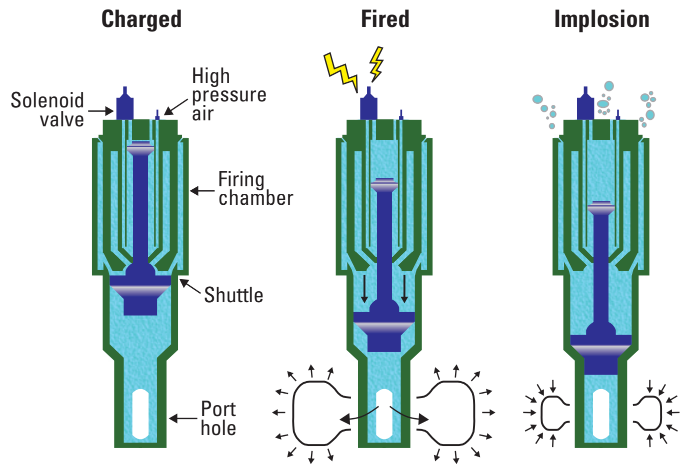


Figure 1. Water gun firing schematic (diagram redrafted from Layhee and others, 2013).

Purpose and Scope

The purpose of this report is to present results of experiments to measure physical magnitude and extent of the pressure output of up to two seismic water guns in an earthen test pond. The pressure output of the water guns was measured by using hydrophones and underwater blast sensors (UBSs) in a half-acre earthen test pond approximately 6–8 feet (ft) deep. Different equipment and methods were examined to ensure their reliability in high-pressure, underwater environments while maintaining the immediate feedback needed to adjust operations in the field. Data at the earthen pond site were collected during September 2012 and July 2013.

The September 2012 study focused on understanding the basic properties of the pressure field created by the water guns in a confined space (for example, dimensions, magnitude, directionality) as well as serving as a proving ground for data-collection techniques. The July 2013 study consisted of three separate scenarios with motivations and goals outlined below.

Additional single-gun data were collected to improve and further refine the September 2012 data at the same test pond by increasing the data density and narrowing the observed area from a full 360-degree azimuth around the water gun to a 180-degree area of coverage. These data were also used to obtain measurements of the speed of the underwater blast front and the decay of pressure with depth.

During May and June 2013, scientists from the USGS Upper Midwest Environmental Sciences Center (UMESC) conducted several studies on the behavior of invasive Asian carps and selected native species when they were exposed to the firing of the water guns (Romine and others, 2015). Equipment and space constraints prevented the concurrent collection of water gun pressure data and fish behavior data. A scenario was designed to replicate the conditions present during these previous May and June studies for predictive pressure mapping of the fish behavior data collected at that time. These pressure map data will be used to analyze the effect of the water guns on the behavior of the Asian carps.

Finally, a scenario was designed to simulate planned testing at Morris, Illinois. The objective of this scenario was to collect data to evaluate the length and continuity of the pressure barriers created between two water guns at various pressures and distances.

Description of the Study Area

All data collection took place at the UMESC campus in La Crosse, Wisconsin (fig. 2), in a half-acre earthen study pond (designated P-2). The testing pond was constructed for fish studies at UMESC and is lined with a polyvinyl chloride (PVC) geo-membrane and located in unconsolidated sands. The pond is rectangular, roughly 215 ft by 105 ft, with the long axis oriented approximately north-south. The sides of the pond slope at a 45-degree angle to a flat bottom that slopes at a 0.27-degree angle from the north to the south. The pond's depth can be varied by controlling the water level; the depth of the pond during data collection varied from 6.5 ft at the north end to 7.5 ft at the south end. The south end of the pond contains a concrete structure used for draining the pond and a set of concrete stairs extending into the pond (fig. 2).

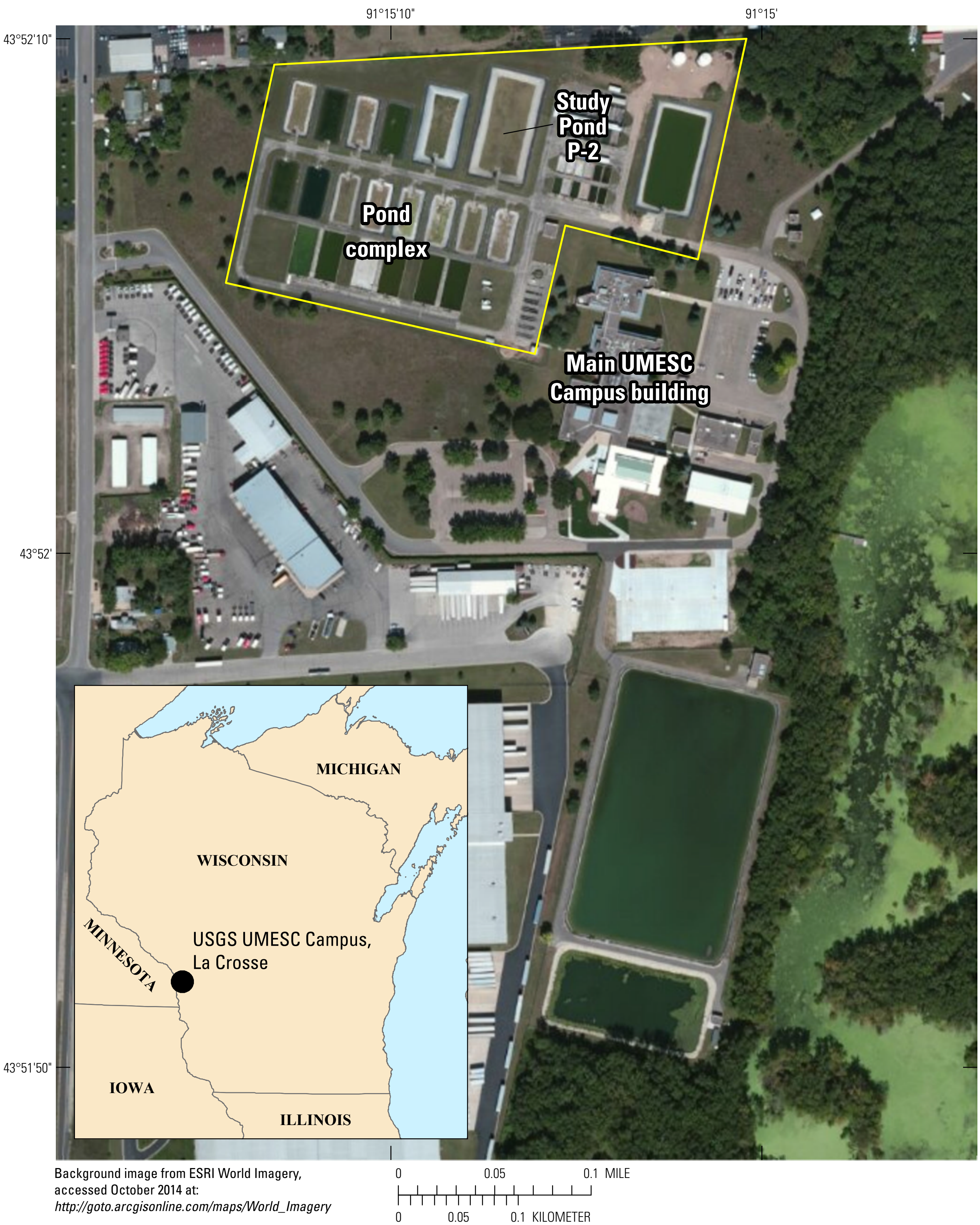


Figure 2. Location of the Upper Midwest Environmental Sciences Center (UMESC), La Crosse, Wisconsin, and location of study pond P-2.

Methods

Data were collected at UMESC in September 2012 and July 2013. Data collection consisted of two separate studies with multiple scenarios and equipment configurations. Each scenario utilized different equipment and survey design to accommodate its individual goals.

Equipment

Up to two 1,310-cubic-centimeter (cm^3) (80-cubic inch [in^3]) water guns (Model S80, U.S. Seismic Systems Inc., Houston, Texas, USA) and one 16-cm^3 (1-in^3) water gun (Model 10B, Bolt Technology, Norwalk, Connecticut, USA) were deployed during these studies. Each water gun was suspended at a depth of 42 inches (in.) from an anchored 2.5- by 5-meter pontoon float. The firing of each water gun was controlled by a HotShot controller (Real Time Systems, Fredericksburg, Texas, USA) tethered to a laptop computer. High-pressure air was supplied to each gun by a high-pressure, high-volume air compressor (WP 4351 compressor [rated at 5,000 lb/in^2 and 81 standard cubic feet per minute], Sauer Compressors USA, Stevensville, Maryland, USA).

Hydrophones are piezoelectric sensors used to determine the increase in pressure from the water guns. The impact of the blast front moving through the water on a quartz crystal produces an electrical voltage in proportion to the pressure increase. The blast hydrophone records only the change in pressure as a result of the water gun firing. It does not record the static pressure. The sensors used were OYO Geospace MP-8D Hydrophones with aftermarket connectors by Instantel. They were sampled at a rate of 8,000 to 32,000 samples per second (sps) by an Instantel Minimate Pro6 Blasting Seismograph. These sensors have a sensitivity of 0.0237 lb/in^2.

Underwater blast sensors (UBSs) are piezoelectric sensors used to determine the increase in pressure from the water guns. The impact of the blast front moving through the water produces an electrical voltage on a tourmaline crystal in proportion to the pressure increase. The UBS records only the change in pressure as a result of the water gun firing. It does not record the static pressure. The sensors used were PCB Piezotronics W138A01 ICP Underwater Blast Sensors being sampled at 8,000 to 32,000 sps by a National Instruments NI-9234 C-DAQ data acquisition system linked to a Windows laptop running National Instruments Labview Signal Express software. These sensors have a sensitivity of 0.02 lb/in^2.

The UBSs and blast hydrophones both monitor pressure, but they have different operational ranges. UBSs are rated to 1,000 lb/in^2 and are suitable for collecting high-pressure data created at closer distances to the water guns. The blast hydrophones are rated to only 47 lb/in^2, but are much more sensitive to the 1- to 10-lb/in^2 range, and they are more suitable to pressures generated at distances generally greater than 30 ft.

For all setups, the water guns were placed in a fixed secured position and depth and fired at a constant pressure. Sensors were suspended in the water column a fixed distance and depth and moved sequentially in the water surrounding the water gun to produce the pressure maps. Five shots were taken at each point location, and the maximum value for all five shots was recorded. The arithmetic mean of the five maximum values recorded at each position was used in the mapping figures.

All acquired data were inspected in the field to ensure successful data collection. Maximum values from hydrophones and UBSs were downloaded directly from the instruments into spreadsheet files and also manually recorded.

September 2012 Study

The September 2012 study consisted of two separate scenarios, a 1-in^3 and an 80-in^3 water gun (fig. 3). Both scenarios had similar goals: Determine the basic characteristics of the pressure field created by the water guns at maximum pressure for each gun, and determine whether any directionality was observed in the pressure field.

The water gun barge was centered both east-west and north-south in the pond, with the water gun suspended so that the ejection ports were at a depth of 42 in. The approximate distance from shore for the water gun was approximately 50 ft east-west and 100 ft north-south. The blast hydrophones were suspended at depths of 1.5 ft, 3.5 ft, and 5.5 ft below water surface (BWS). During the data collection, the hydrophones were advanced across the pond following an approximate 20-ft grid spacing. The hydrophone measurements were confined to the approximately 80-ft-wide center section of the approximately 105-ft-wide pond to ensure that the measurements were made over the approximately flat portion of the bottom of the pond rather than the sloped edges. Measurements were made in a square-wave-type pattern with the hydrophones being advanced to the east or west extent of the flat pond surface. The hydrophones were then moved 20 ft in the north-south direction to establish a new east-west-trending sampling section. This pattern was repeated four times before the hydrophones became too close to the water gun to be operated safely. UBS data were collected to quantify the area within the remaining area surrounding the water gun. This constituted 1 iteration consisting of 16 areal data points with a value for each of the 3 tested depths.

The Model 10B 1-in^3 water gun scenario consisted of a single iteration on the northern end of the pond. The 1-in^3 water gun was suspended vertically beneath the barge with the four ejection ports at a depth of 52 in. These ports were arranged in a ring attached to the bottom of the cylindrical water gun. One of the ports faced directly toward the north end of the pond. All data points were collected at 1,500 lb/in^2 (the maximum operating pressure for the 1-in^3 water gun).

The magnitudes of the pressure values (less than 5 lb/in^2 at less than 30 ft) collected for the 1-in^3 water gun after 1 iteration of 16 positions were sufficient to eliminate it as a viable gun for creating a large-scale barrier. Testing proceeded to the 80-in^3 water gun scenario.

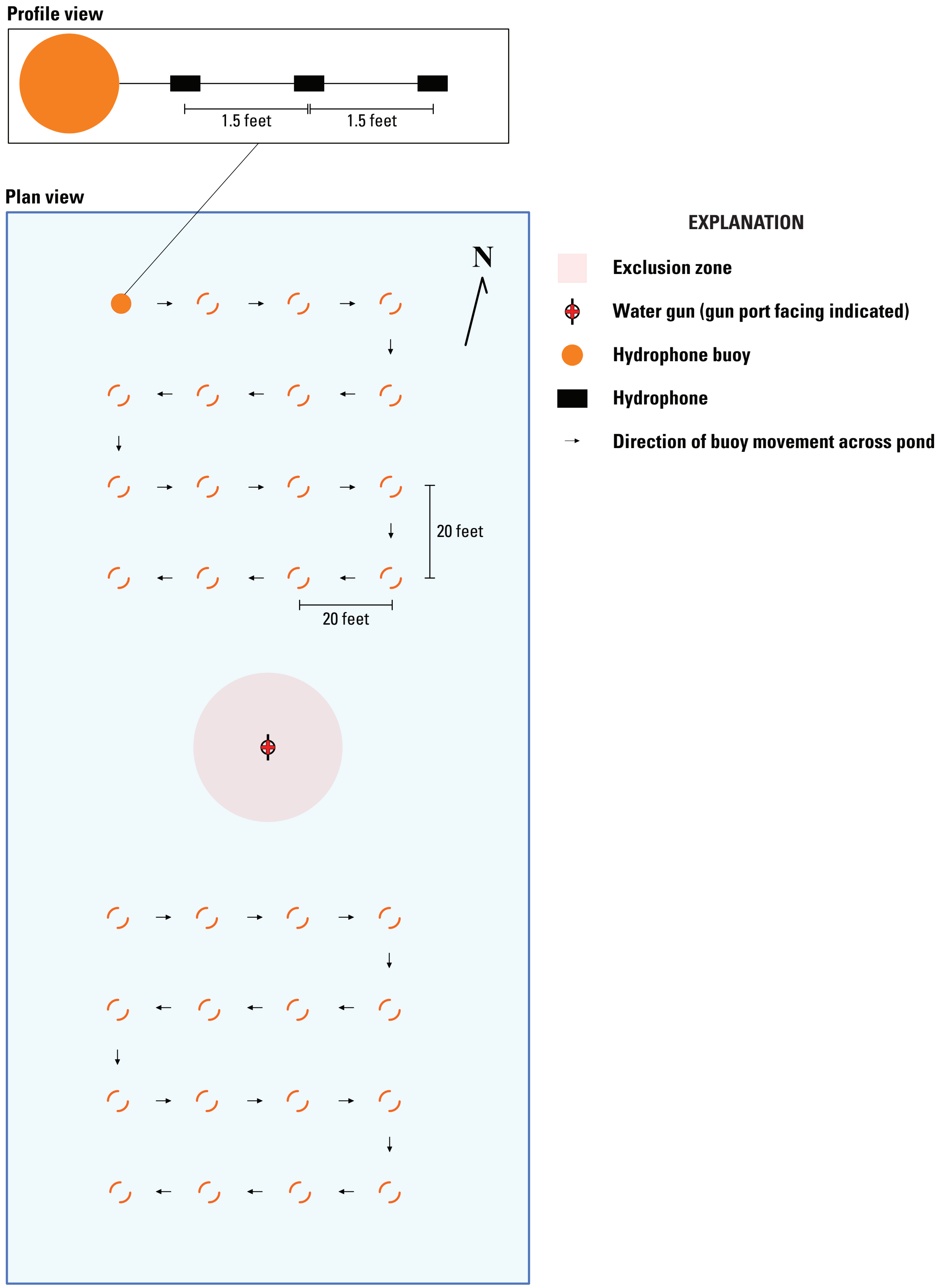


Figure 3. Data locations for 80-cubic-inch water gun scenario in September 2012. Red water gun indicator shows the alternate orientation of the gun ports.

The S80 80-in^3 water gun scenario consisted of four iterations of 16 positions performed on both the north and south ends of the pond at a pressure of 2,000 lb/in^2 (the maximum operating pressure for the 80-in^3 water gun). The 80-in^3 water gun was suspended horizontally beneath the barge with the two ejecting ports at a depth of 42 in.

The orientation of the water gun and resulting direction of the ejection ports was changed after two iterations because of possible variation in energy output. The ports faced east-west for the first two iterations, one each on the north and south ends of the pond. They faced north-south for the last two iterations, one each on the north and south ends of the pond. When all four groups are plotted with the water gun held in a fixed orientation, the four groups produce a figure with full azimuthal coverage around the water gun, which aids in evaluating the directionality of the water gun.

The location data from the rangefinder were recorded in field notebooks from at least four stations located around the pond for each hydrophone position. During processing, an x-y grid was centered on one of these stations and trigonometric and geometric identities were used to locate all of the other locations relative to this point.

July 2013 Study

Three separate scenarios were used for the July 2013 data collection:

1. Fish behavior: Two 80-in^3 water guns were set up in the UMESC pond to simulate the water gun and equipment setup used during the May and June 2013 fish behavior experiments.
2. Single gun assessment: One 80-in^3 water gun was located and fired in the pond to build on the September 2012 work by better defining the resolution of the horizontal and vertical distribution of pressure.
3. Experimental barrier assessment: Two 80-in^3 water guns were located in the pond to approximate the testing setup of a barrier width scenario planned for Morris, Illinois.

To hasten data collection and better spatially locate the hydrophones and UBSs, all underwater hydrophones and UBS were suspended from a 40-ft-long PVC boom (fig. 4) that would pivot radially from the approximate water gun location. Five groups of three sensors each were suspended beneath

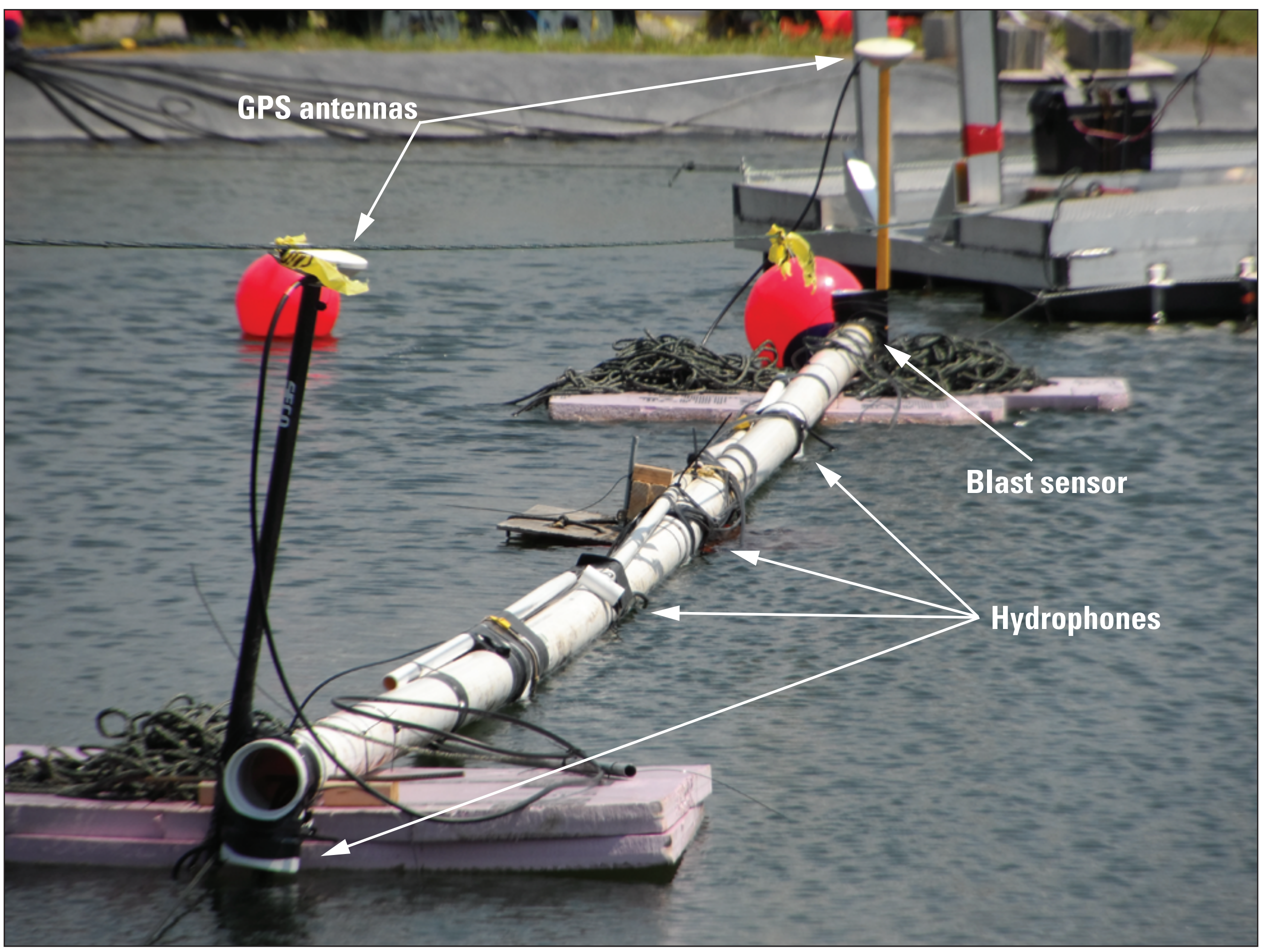


Figure 4. Photo showing hydrophone boom with GPS antennas, hydrophone positions, and blast sensor position indicated.

this boom, with an even horizontal spacing of 10 ft. The sensor group closest to the water guns contained the UBSs; the remaining groups were blast hydrophones. To produce the five data locations from the two GPS receivers, the data were first converted from latitude/longitude format to Universal Transverse Mercator (UTM) coordinates. The two farthest equipment locations along the receiver boom were determined by using the GPS data. The remaining middle three equipment locations were determined on the basis of the measured 10-ft distance between locations.

Processed location data were integrated with the average maximum values obtained from each data point. These data were contoured by using Esri® ArcGIS ArcMAP® (Esri, Inc., 2013). A kernel smoothing with barriers algorithm was used to create pressure maps within the hydrophone and UBS boundaries on each side of the water gun. This kernel interpolation model fits a first order polynomial, within specified overlapping neighborhoods, to produce the mapping output, limiting instability by using methods similar to ridge regression to estimate the regression coefficients.

Fish Behavior Scenario

Two 80-in^3 water guns were on an east-west line located 145 ft south of the northern pond edge; separation between the water guns was approximately 50 ft. The gun ports for both guns were set at 42 in. BWS and aligned east-west. Both water guns were fired at 1,300 lb/in^2. Water gun position was established by GPS receivers mounted on the barges supporting the water guns. UBSs were located 20 ft perpendicularly north (or south) from the east-west line formed by the two water guns, with the hydrophones at 30, 40, 50, and 60 ft from the gun. Each hydrophone and blast sensor lateral position was recorded at depth settings of 1.5, 3.5, and 5.5 ft (fig. 5).

The PVC boom suspending the sensors was aligned perpendicularly to the east-west gun line and then moved across the pond from east to west in approximately 10-ft increments, keeping the distance between the end of the boom and the east west gun line fixed. This iteration was done first on the southern side of the east-west gun line and then on the north side (fig. 6).

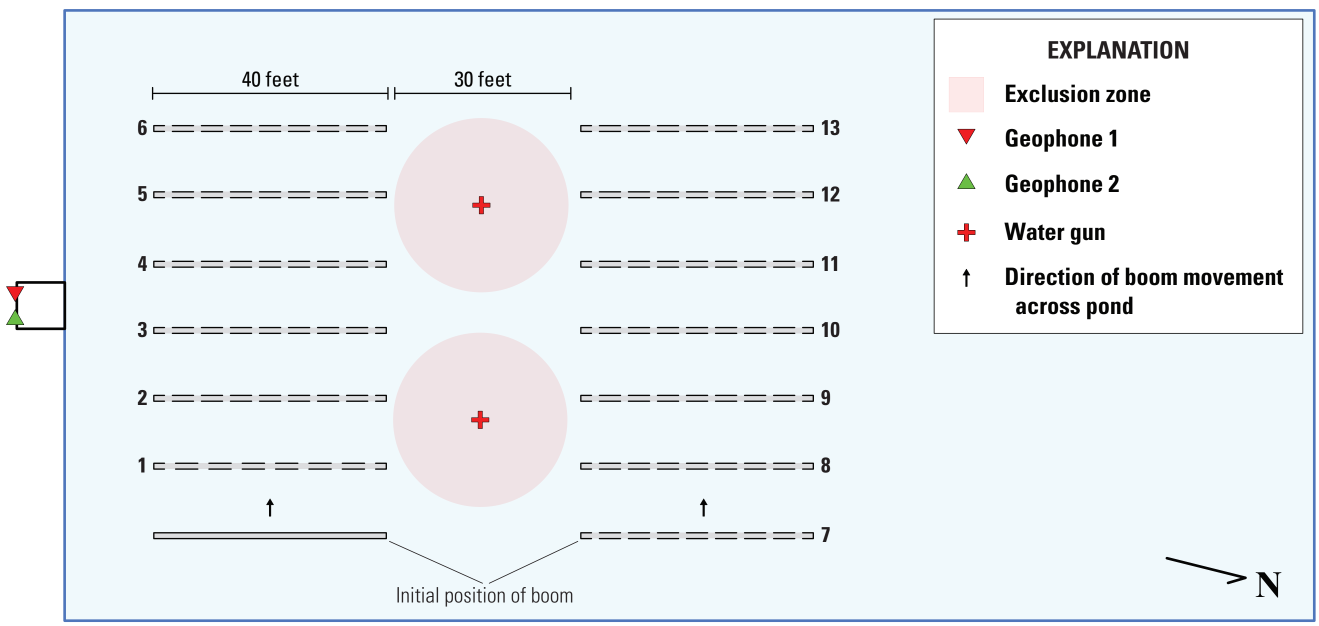


Figure 5. Equipment setup for the fish behavior scenario.

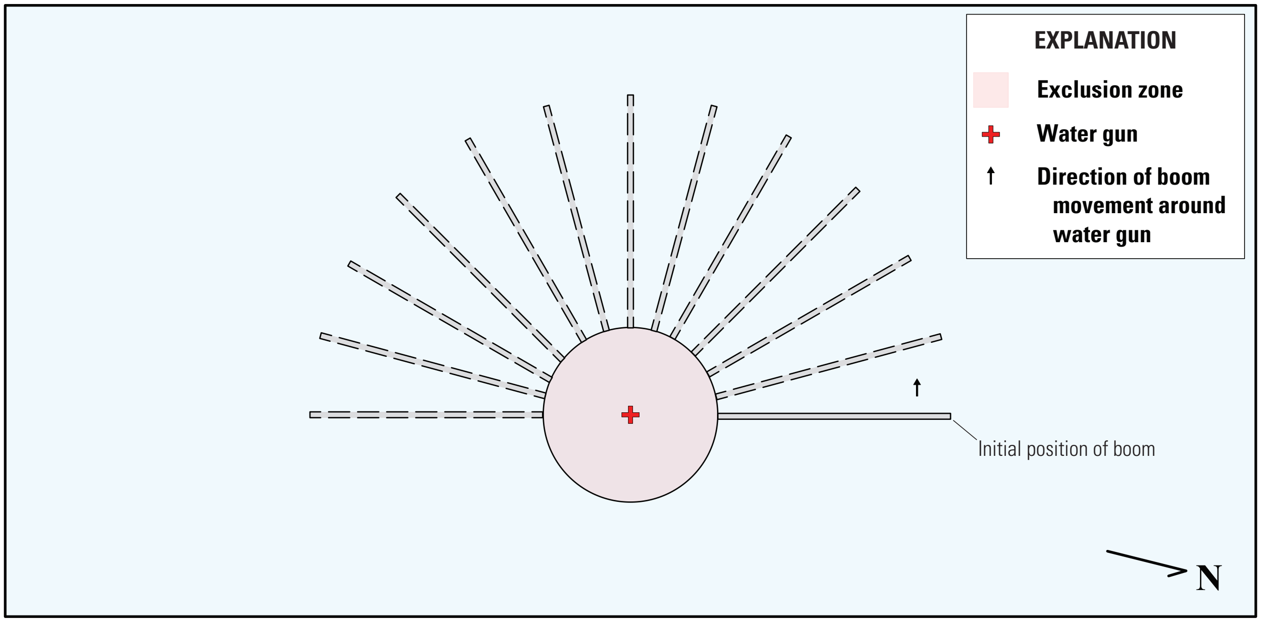


Figure 6. Equipment setup for the single gun assessment scenario.

Single Gun Assessment Scenario

The 80-in^3 water gun was fixed in the center of the pond (approximately 110 ft) in the north-south direction and 30 ft from the eastern wall. The gun ports were at a depth of 42 in BWS and aligned east-west.

The PVC boom was initially oriented north-south parallel to the east wall. The end supporting the UBS was anchored to a pivot point on the barge supporting the water gun. From this initial position, the PVC boom was swung radially around the water gun at 15-degree increments. The UBS was 15 ft from the water gun, and the hydrophones were 25, 35, 45, and 55 ft from the water gun. The sensors were initially hung at depths of 1, 2, and 3 ft. With the sensors at this initial depth setting, the boom was swung through 13 positions at increasing angles of 15 degrees to complete a 180-degree rotation around the water gun barge, with five firings of the water gun collected at each position. Once the boom was facing south with its length parallel to the east wall, the sensors were repositioned to depths of 4, 5, and 6 feet BWS. The boom then was swung back, collecting data at the same 15-degree rotation increment to return to the original, north-facing position (fig. 6). This process constituted one iteration of this scenario.

This scenario consisted of four trials. The first, second, and fourth trial were varied by adjusting the gun pressure to 1,000, 1,500, and 2,000 lb/in^2 respectively. In the third trial, water gun pressure was 1,300 lb/in^2, but the gun was suspended vertically and the gun port maintained at a depth of 42 in.

Experimental Barrier Assessment Scenario

The experimental barrier assessment consisted of two 80-in^3 guns separated by an initial distance of 99 ft. Hydrophones were suspended at the midpoint between the two guns. Hydrophones were at fixed depths of 1.5, 3.5, and 5.5 ft. Data for several iterations were collected by expanding the distance between the two guns by 5 ft, moving each gun 2.5 ft to keep the hydrophones centered, and varying the pressure of the water guns (fig. 7).

Pressure was varied only on the first distance, 99 ft. A pressure of 1,300 lb/in^2 is easier for the air compressor to maintain when supporting two 80-in^3 water guns firing every 10 seconds; 1,600 lb/in^2 is the operational maximum. Testing at 1,300 lb/in^2 indicated that the 5-lb/in^2 target value was not possible to maintain across the water boundary. All of the other iterations were tested at 1,500 lb/in^2.

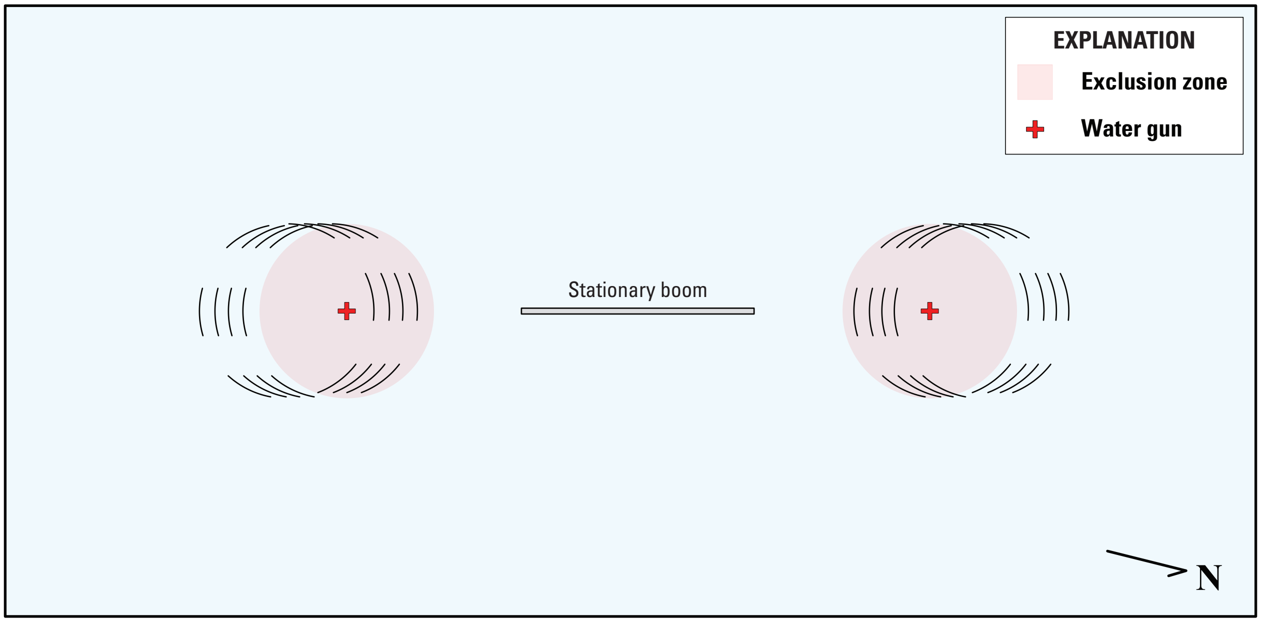


Figure 7. Equipment setup for the experimental barrier evaluation scenario.

Changes for the Experimental Barrier Evaluation Scenario

These data were contoured using a kriging algorithm with a search length containing the entire dataset; Surfer® by Golden Software was used to produce figures indicating the pressure intensity at locations within the pond. Kriging is a linear interpolation algorithm used to solve a system of linear equations to estimate the value of a regionalized variable at a specific point in a random data field. A specific point value is a weighted average of the values of that function at nearby points with the weights assigned based on distance from the chosen point. A solution is found by iterating to minimize the variance of the data weights.

The water guns were fired simultaneously, or as close as possible with the equipment limitations, during each data collection period. Because of minor timing variations in the gun triggering system, each interaction of the two blast fronts is unique. Therefore, each figure shown in the Results section for this setup represents only the maximum values from a single firing of the water guns, unlike the arithmetic mean of the five maximum shots shown in figures for the other scenarios. Each figure for this setup represents the shot in which the pressure waves met closest to the midpoint between the two guns of the 3–5 shots taken at each position. The procedure was changed in this instance to prevent the artificial improvement of the barrier due to the effects of the averaging process. Averaging the results as done in previous trials would increase the extent of the 5-lb/in^2 zone artificially because the area where the barrier was below the 5-lb/in^2 target value was not consistent between individual water gun firings. Averaging these data would then extend the 5-lb/in^2 target area across areas that would not have reached that value on any single water gun firing.

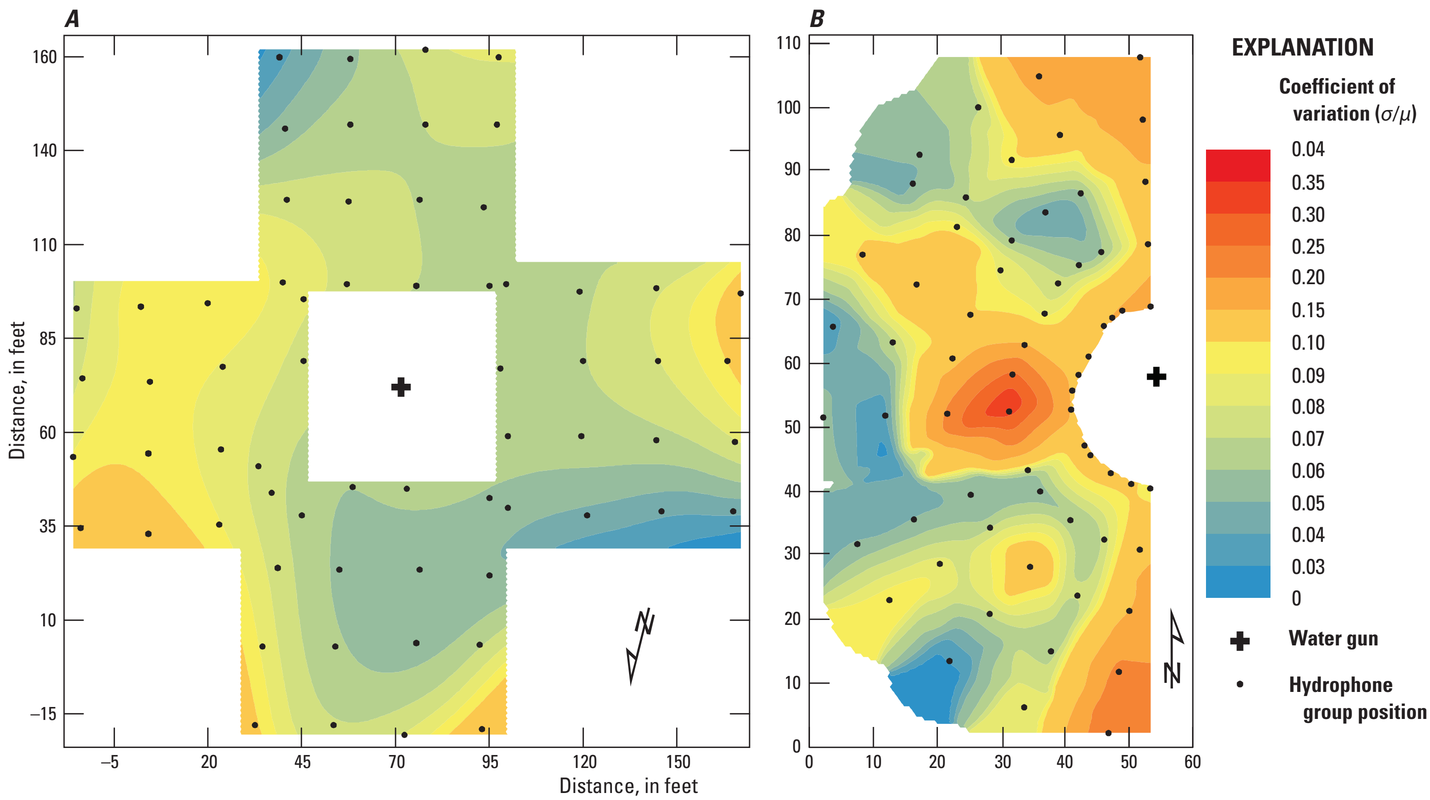


Figure 8. Comparison of two maps showing the spatial distribution of the standard deviation for each five-shot grouping for experiments in September 2012 (*A*) and July 2013 (*B*).

Results

The following sections of the report are illustrated with selected pressure maps of the pond, grouped by study and scenario. These pressure maps (and several additional figures) are also presented in appendix 1, in sequential order, to facilitate comparison among the different scenarios and studies.

Except for the experimental barrier scenario, all of the pressure maps in this report show data points that are derived from an arithmetic mean of the five maximum values recorded at each position. Figure 8 shows plots of the standard deviation of those five-shot groupings for the September 2012 and July 2013 experiments. Standard deviations for these groupings increase in close proximity to the water gun firing port and to structures in the testing pond such as the sloped wall of the pond and the concrete filling structures in the south end of the pond.

September 2012 Study

1-Cubic-Inch Water Gun Scenario

Data for the 1-in^3 water gun scenario are not depicted in this report, primarily because the grid spacing and depth settings were insufficiently dense to record the extent of the 5-lb/in^2 target value given the much smaller extent of that area compared to that for the 80-in^3 gun. The differences among the three depth settings indicate that the blast front produced by the 1-in^3 gun is omnidirectional in terms of the horizontal distribution of pressure but planar in the vertical dimension, with lower pressures above (1.5 ft BWS) and below (5.5 ft BWS) the plane intersecting the gun ports (3.5 ft BWS). The 5-lb/in^2 threshold was not met in the area sampled, but the middle depth setting, 3.5 ft, showed a pressure value over

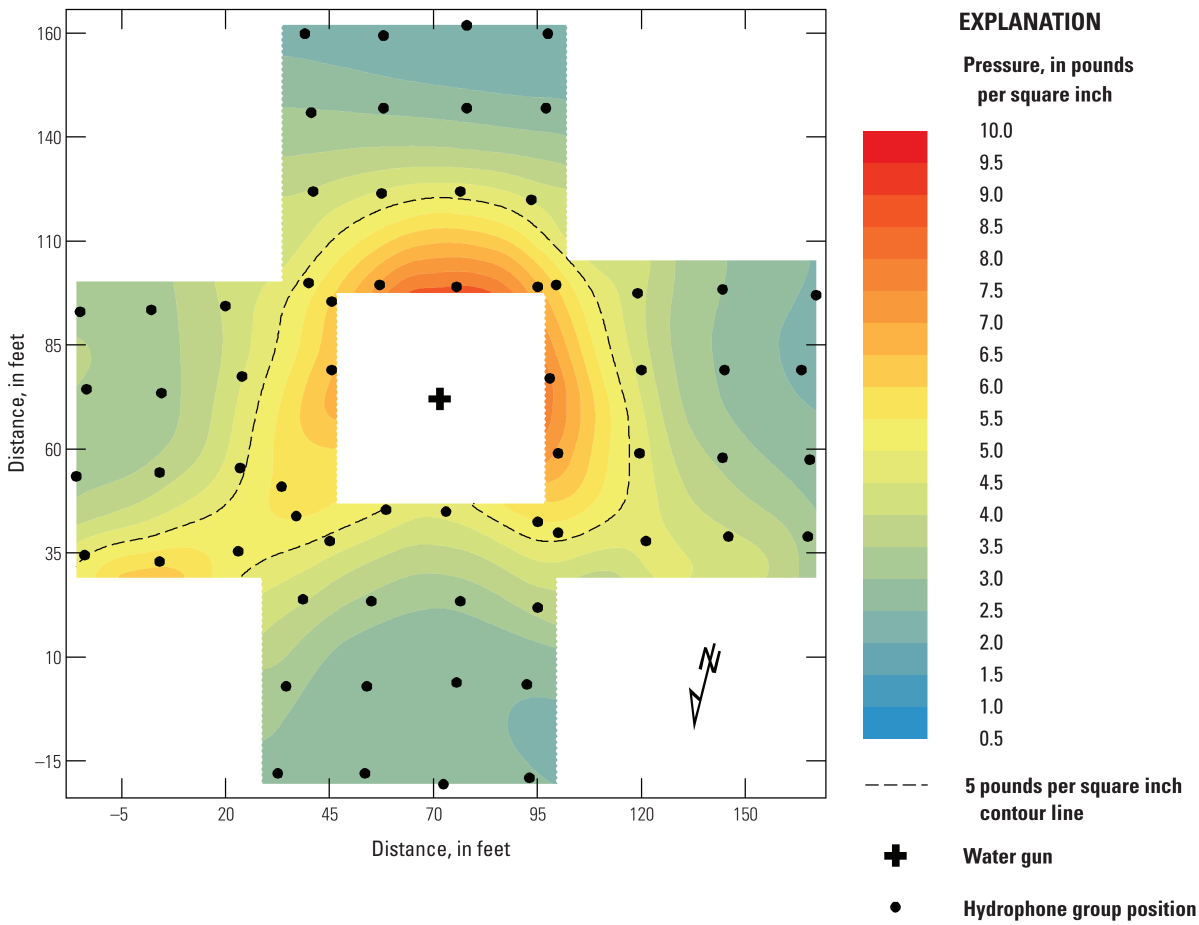


Figure 9. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 1.5 feet.

3 lb/in^2 out to a distance of approximately 65 ft from the water gun. Ultimately, the extent of the pressure field produced by the 1-in^3 water gun was not large enough to justify the continuation of experiment.

80-Cubic-Inch Water Gun Scenario

The 80-in^3 water gun setup was run as four separate iterations that were then integrated to produce figures 9–11. Data were collected on both sides of the pond with the gun ports aligned east-west, then north-south. When the data-sets are combined, the result is the cruciform pattern shown in figures 9–11.

Pressure maps for three separate depths (figs. 9–11) show variations for depth above, below, and at the level of the water gun. The depths above and at the water gun's depth show the greatest radial pressure extent, with the 5-lb/in^2 target level extending to approximately 45-ft radius around the gun's position. The data from the 3.5-ft depth have both the highest pressure (12 lb/in^2 approximately 35 ft from the water gun) and the greatest radial extent of the 5-lb/in^2 target level with that level extending to an approximately 45-ft radius around the gun's position. Data from the 1.5-ft and 5.5-ft depth show both lower maximum pressures and smaller radii of the 5-lb/in^2 target level, owing to their greater vertical distance from the water gun (water gun depth, 42 in).

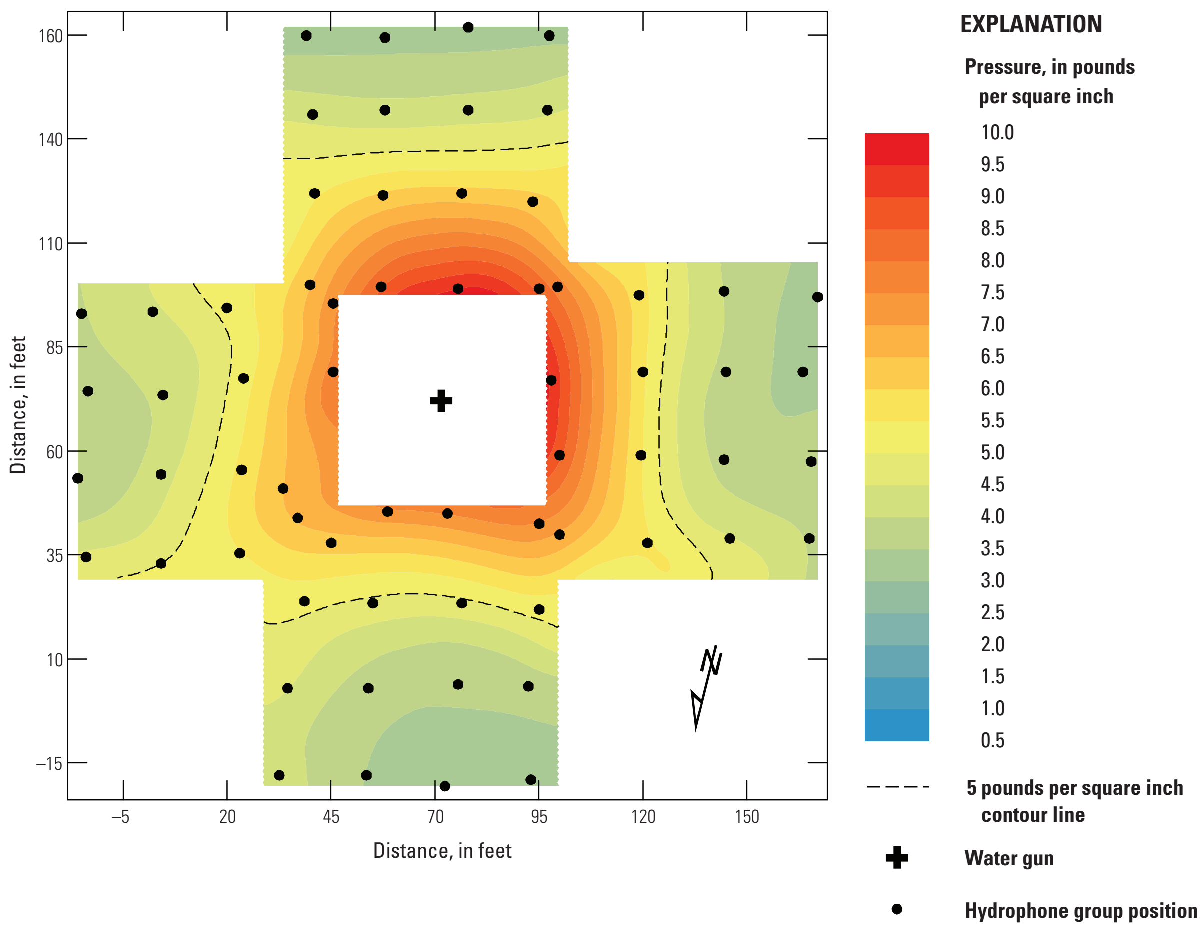


Figure 10. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 3.5 feet.

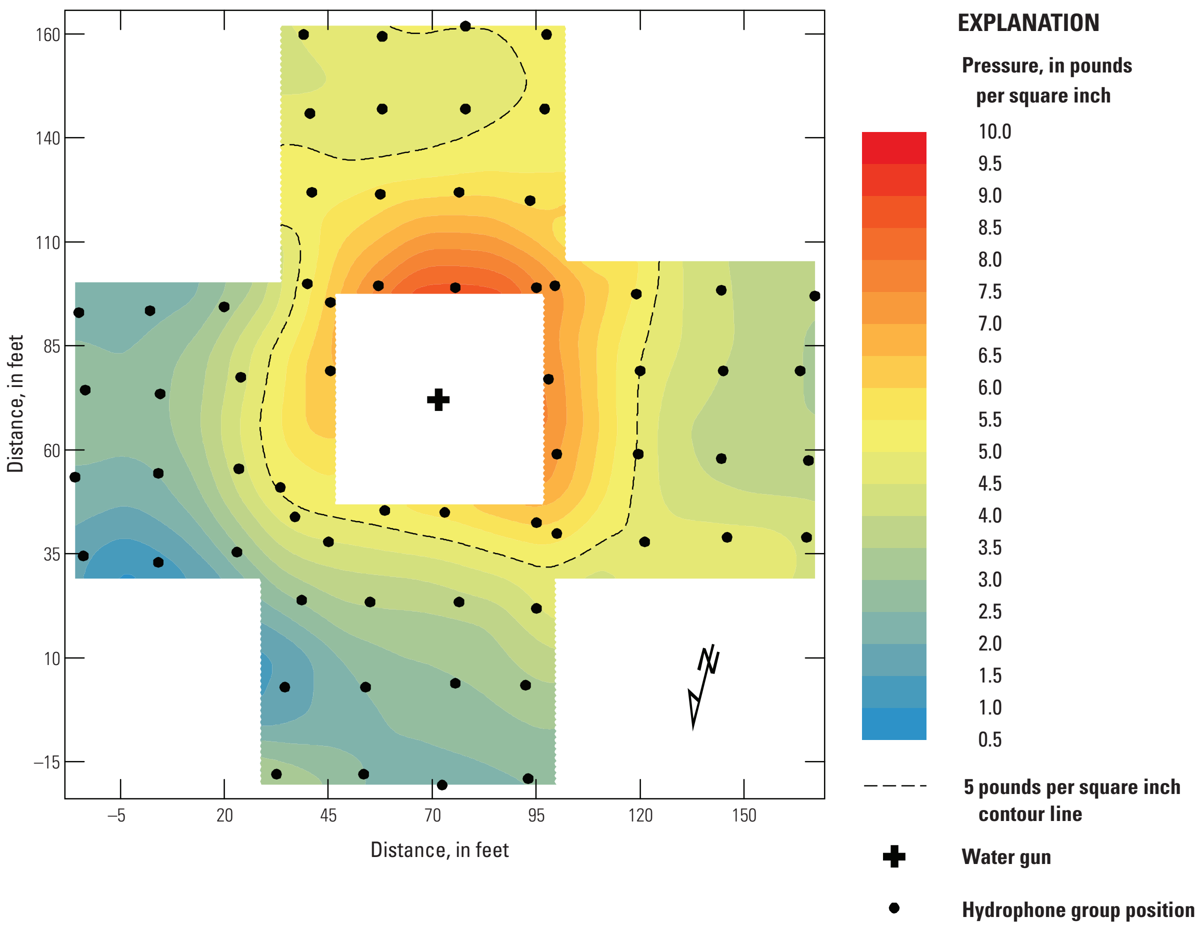


Figure 11. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 5.5 feet.

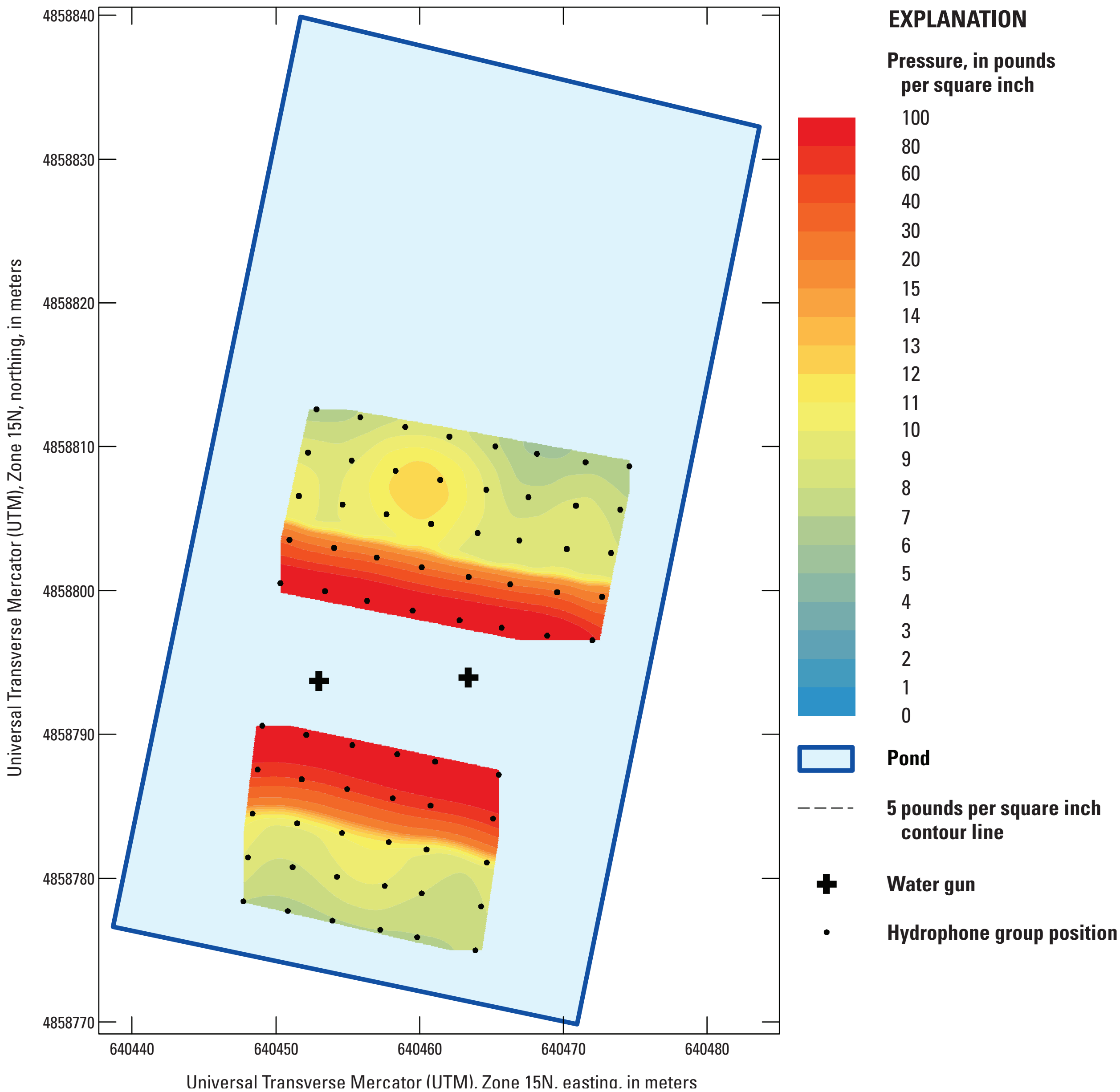


Figure 12. Pressure map from two 80-cubic-inch water guns fired at 1,300 pounds per square inch, measurements at a depth of 3.5 feet.

July 2013 Study

Fish Behavior Scenario

The fish behavior scenario was run as a single iteration with fixed depth settings for hydrophones at 1.5, 3.5 and 5.5 ft BWS. Data were collected across a roughly 10-ft grid both north and south of the line of two guns. No data were collected at the center of the two guns because concerns about exceeding the pressure limits of the blasting hydrophones.

Comparisons of data in roughly similar locations relative to the locations of the water gun's firing port show that adding a second gun results in roughly twice the pressure compared to a single gun (see figs. 12 and 15). Similarly, increases in pressure with depth correlate closely with the single gun results. Pressure increases with depth, but the magnitude of the difference among each depth is proportional to the number of guns.

Single Gun Assessment Scenario

The single gun assessment scenario was run as four separate trials; horizontal gun at 1,000, 1,500, and 2,000 lb/in^2, and vertical gun at 1,300 lb/in^2. Each trial consisted of one 180-degree iteration with the hydrophones at 1, 2, and 3 ft BWS and one 180-degree iteration with the hydrophones at 4, 5, and 6 ft BWS.

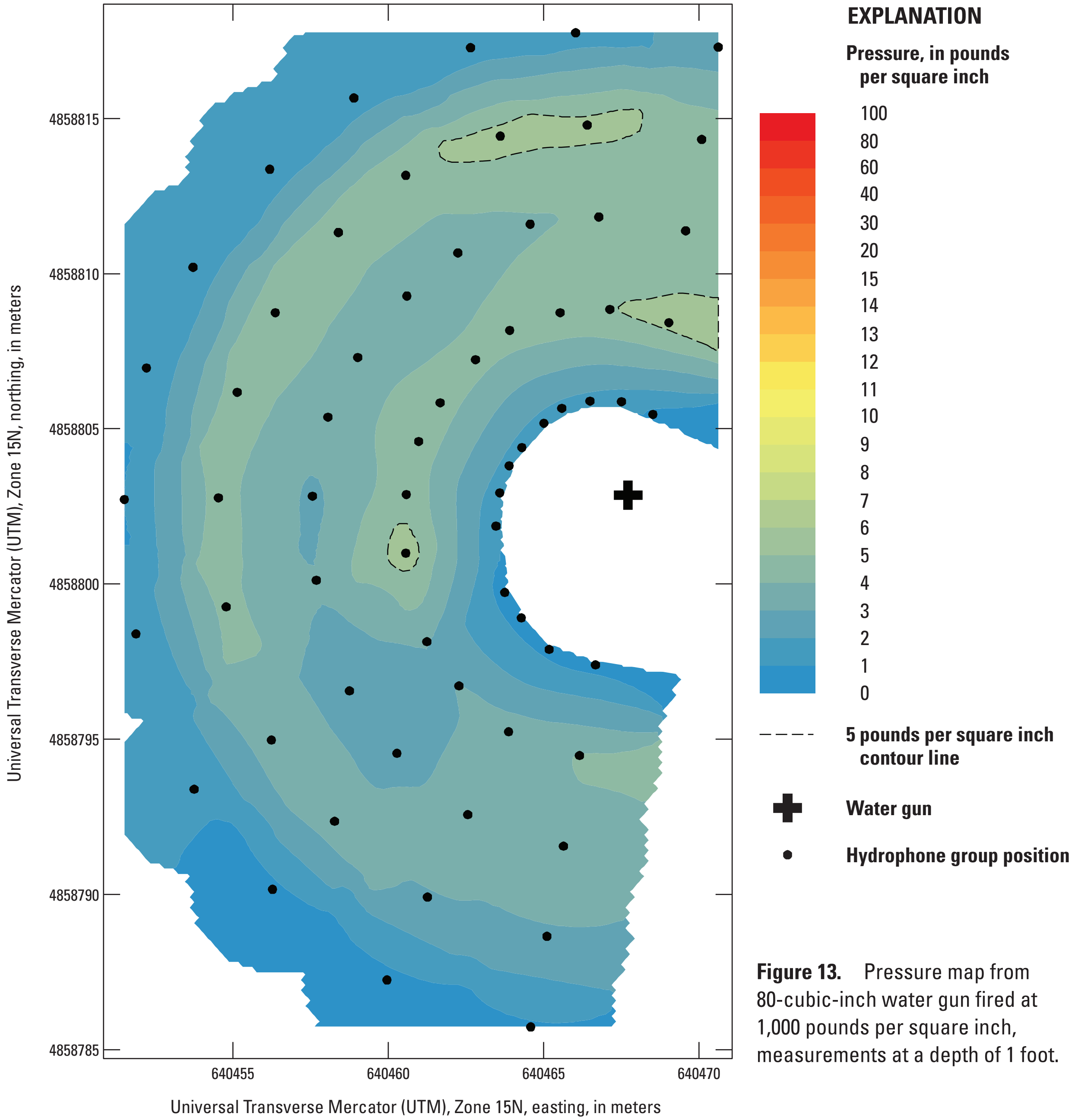


Figure 13. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 1 foot.

Trials 1, 2, and 4 differed only in the pressure setting of the water gun. Each of these trials showed broadly similar results both with each other and with the 80-in^3 gun scenario in the 2012 study. Pressure increased with depth, and the greatest radial extent of the pressure field occurred at the depth closest to the firing ports on the water gun.

The increased data density highlighted several features not evident on the 2012 scenario. The radial extent of the 5-lb/in^2 pressure gradient exceeds the 45-ft limit identified in the 2012 scenario at depths close to the firing ports (independent of firing pressure), but this radius is sharply reduced by small increases or decreases in depth. Data appear to be affected by boundary conditions. During trials 1, 2, and 4, there was a large decrease in the overall pressure gradients between 4 ft BWS and 5 ft BWS (figs. 16 and 17). This was followed by a small, localized increase in the area immediately surrounding the gun at 6 ft BWS (fig. 18). This area of increased pressure appears to be due to spreading of the pressure front on impact with the bottom or a reflection off the bottom. Similar interactions with the bottom of the pond also appear on several of the maps where the bottom seems to be reducing the strength of the pressure field in a roughly 45-degree arc southwest of the water gun.

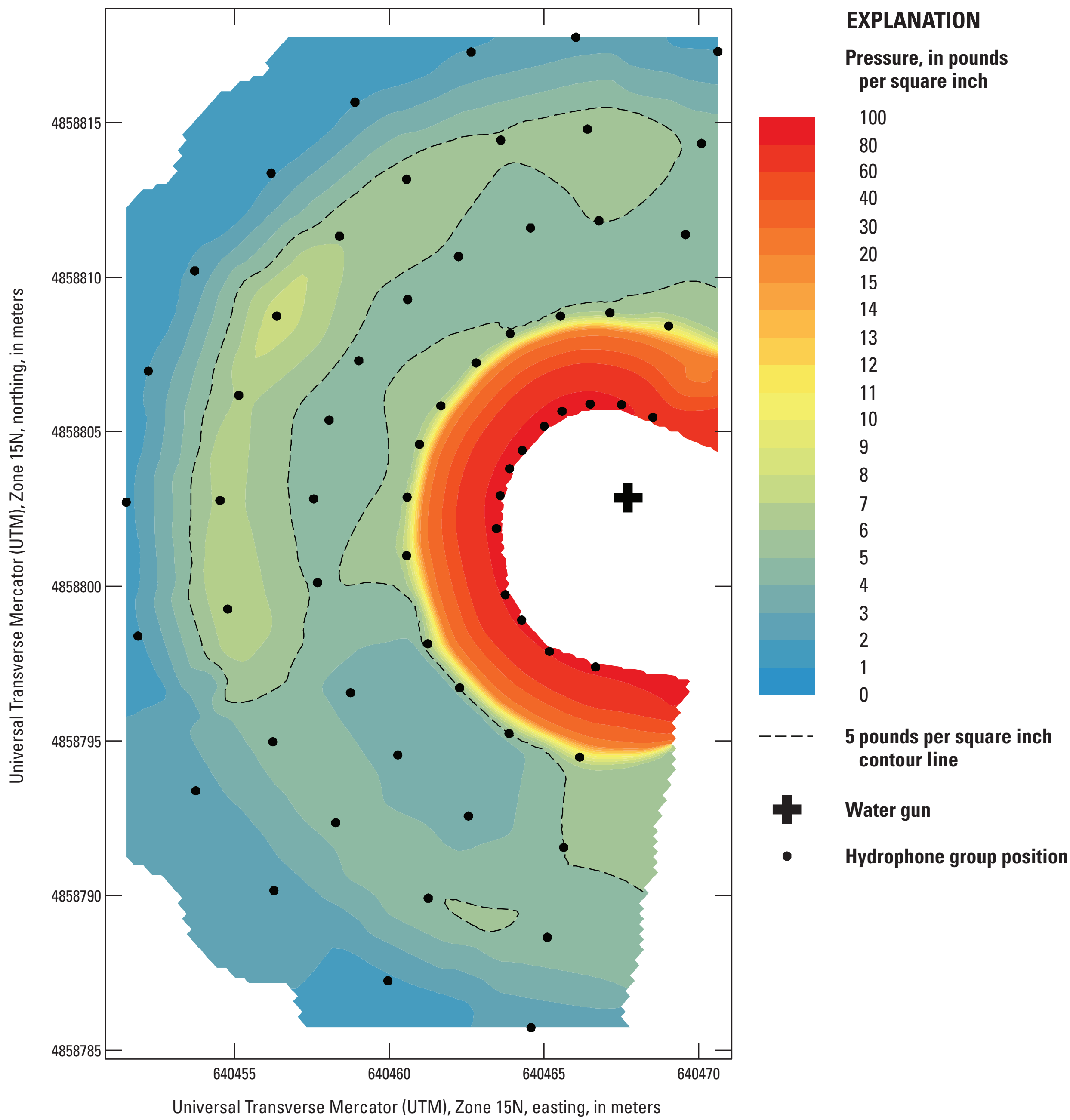


Figure 14. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 2 feet.

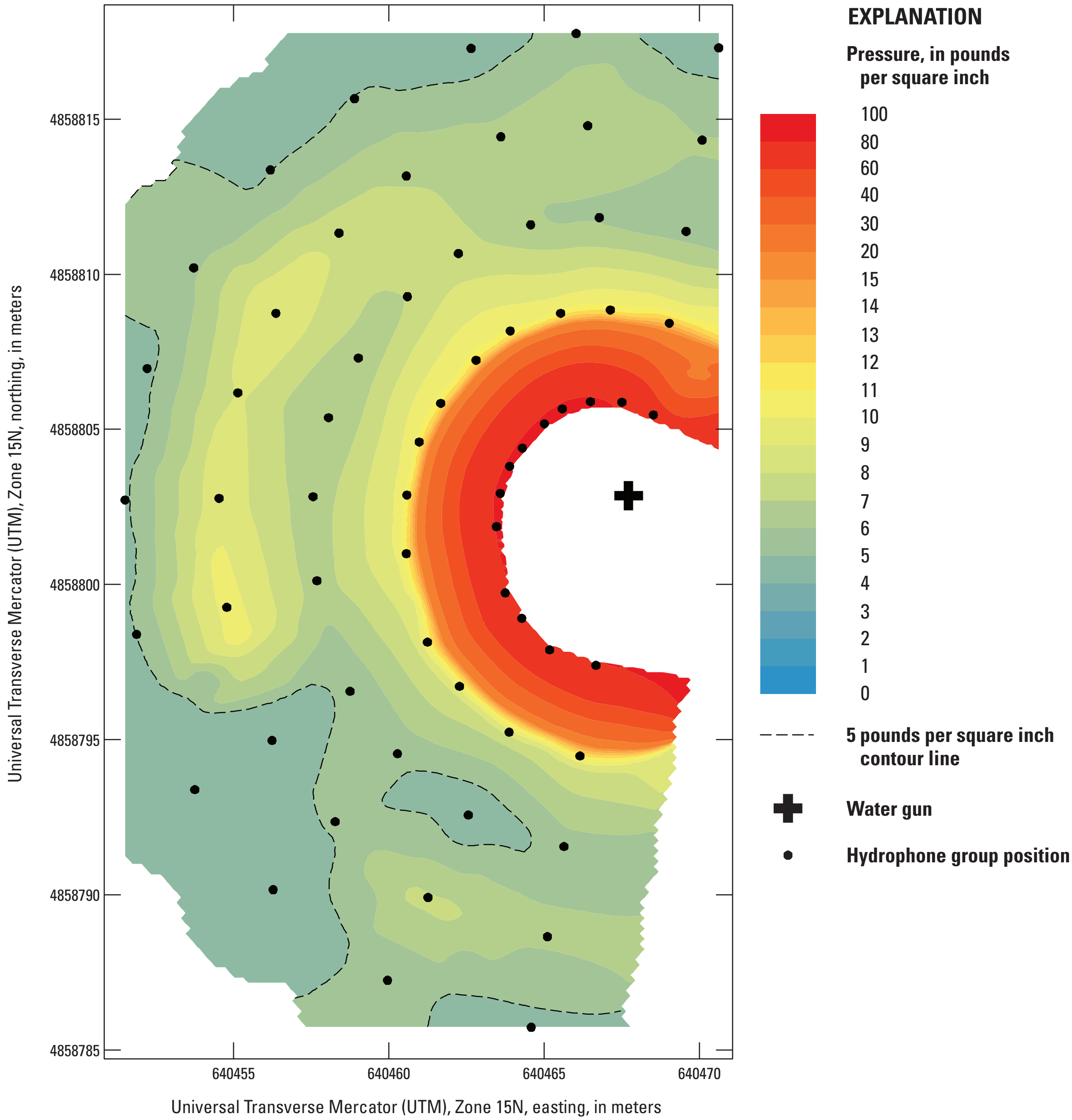


Figure 15. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 3 feet.

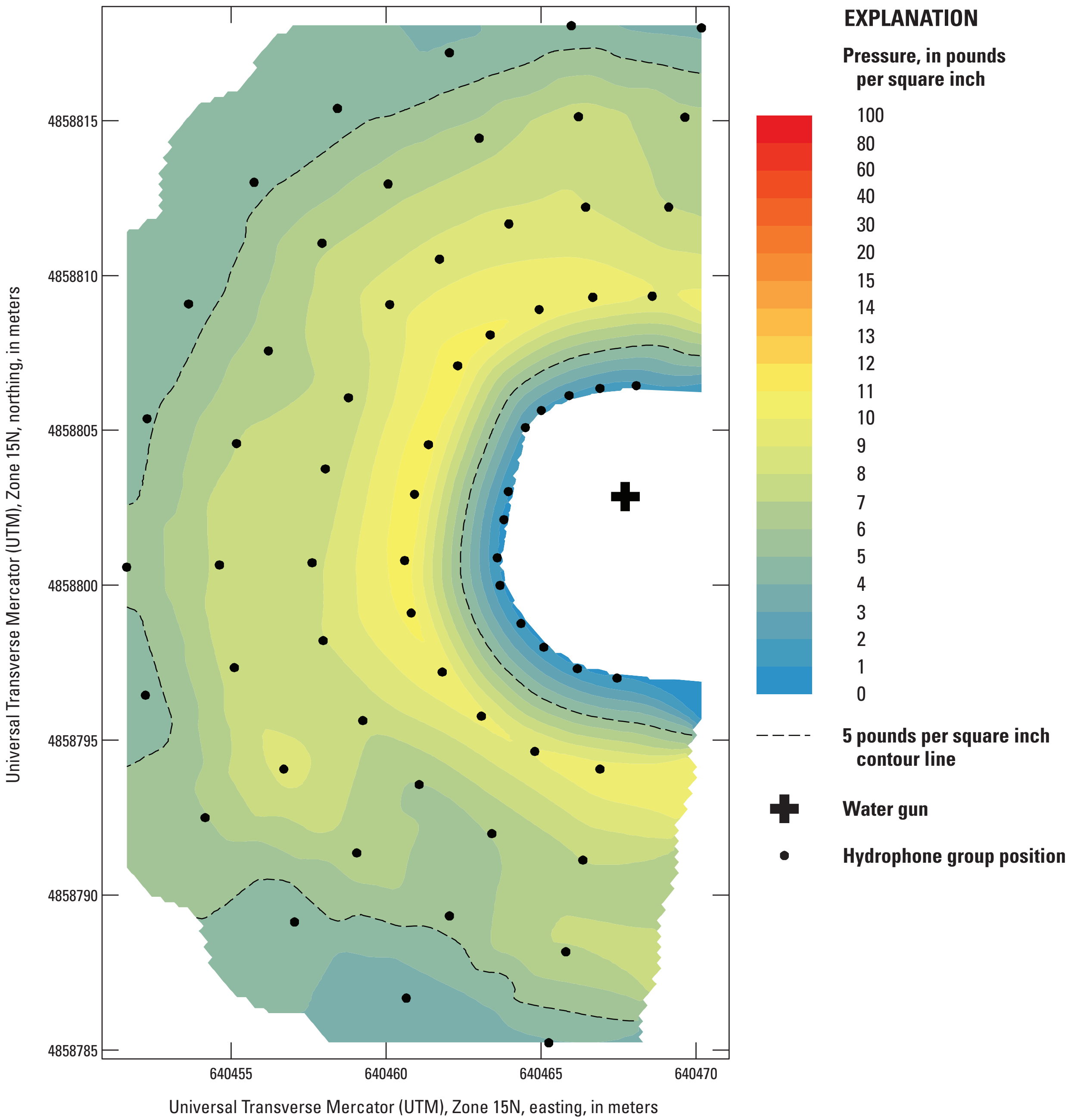


Figure 16. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 4 feet.

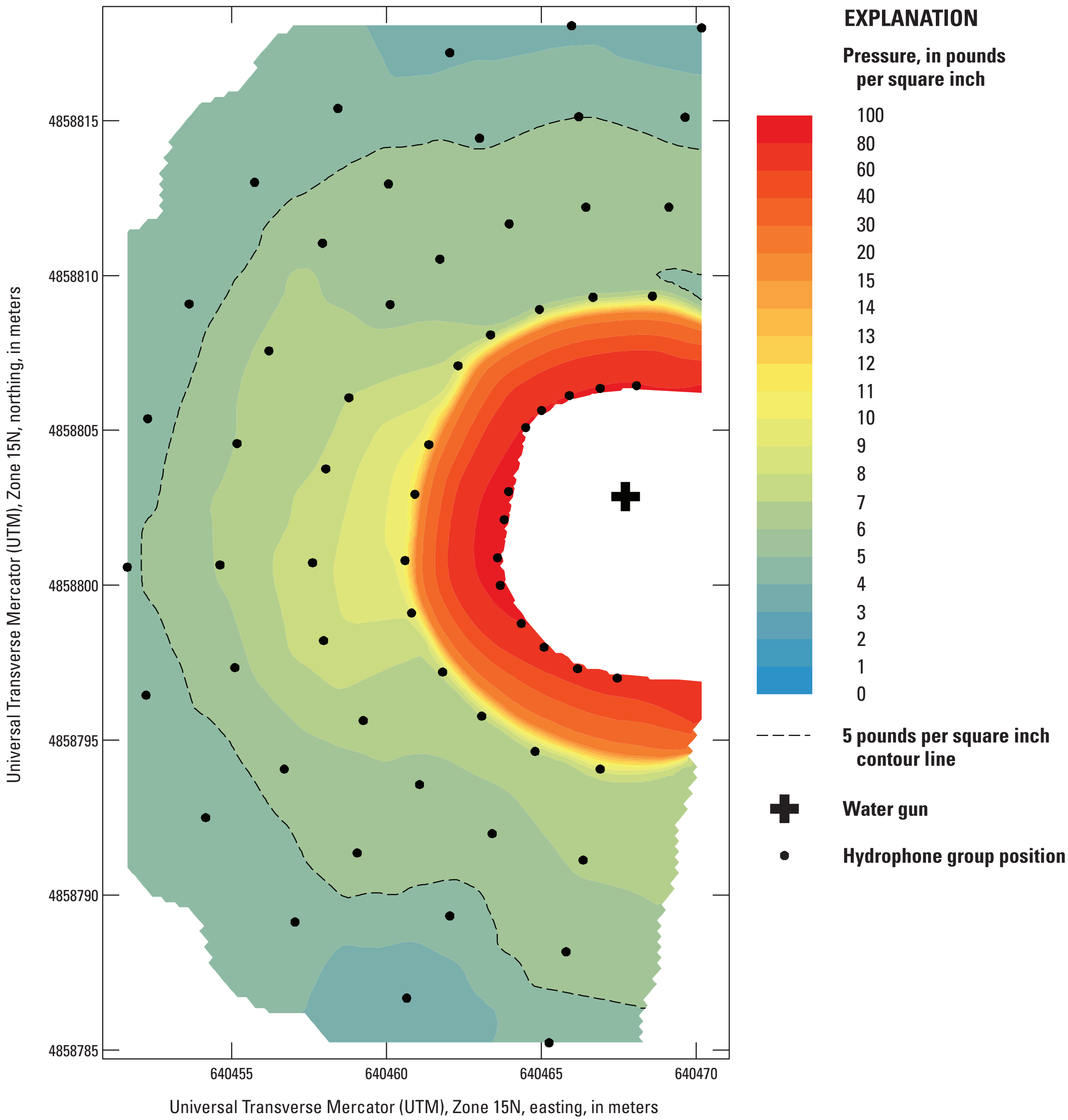


Figure 17. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 5 feet.

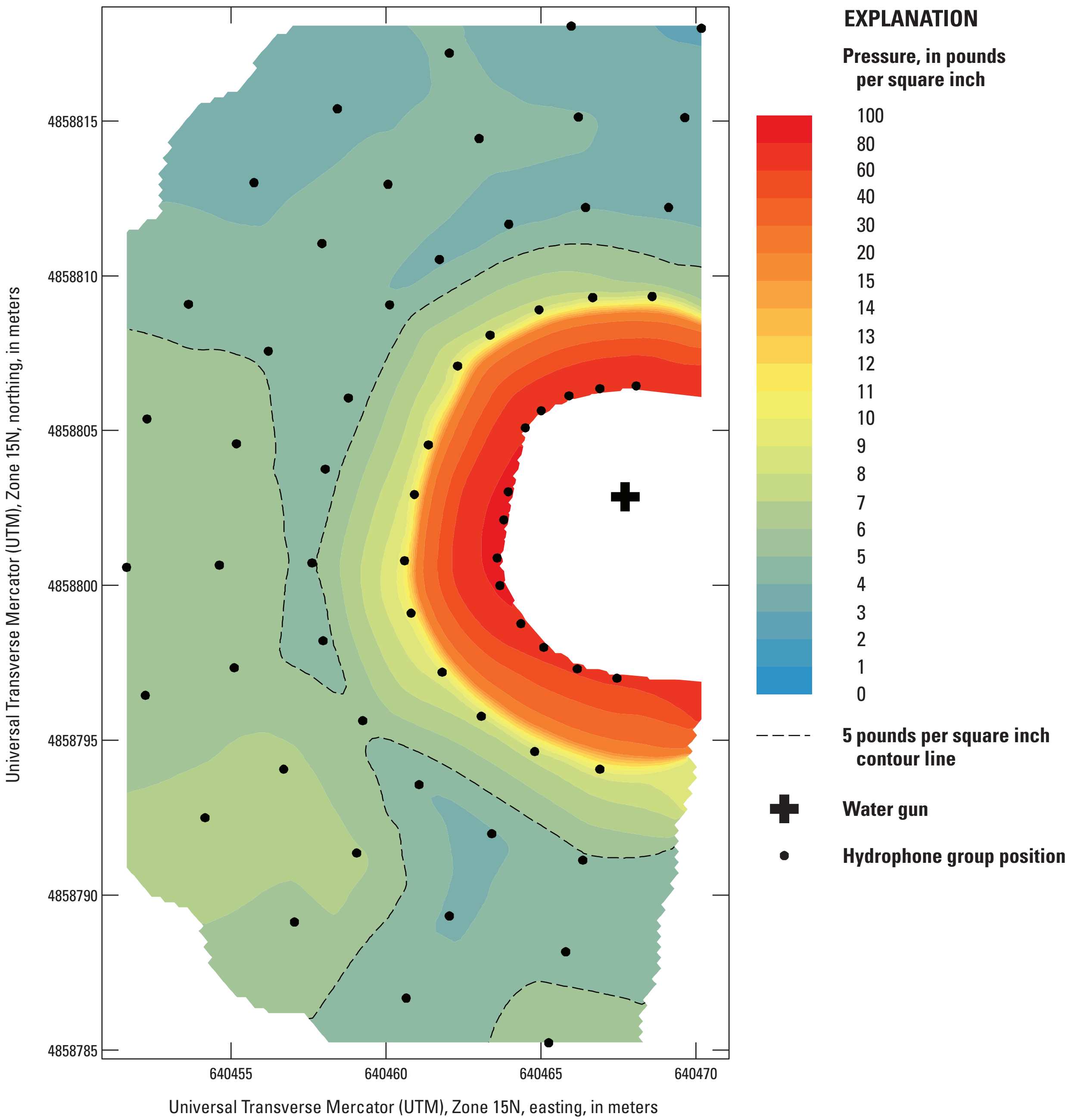
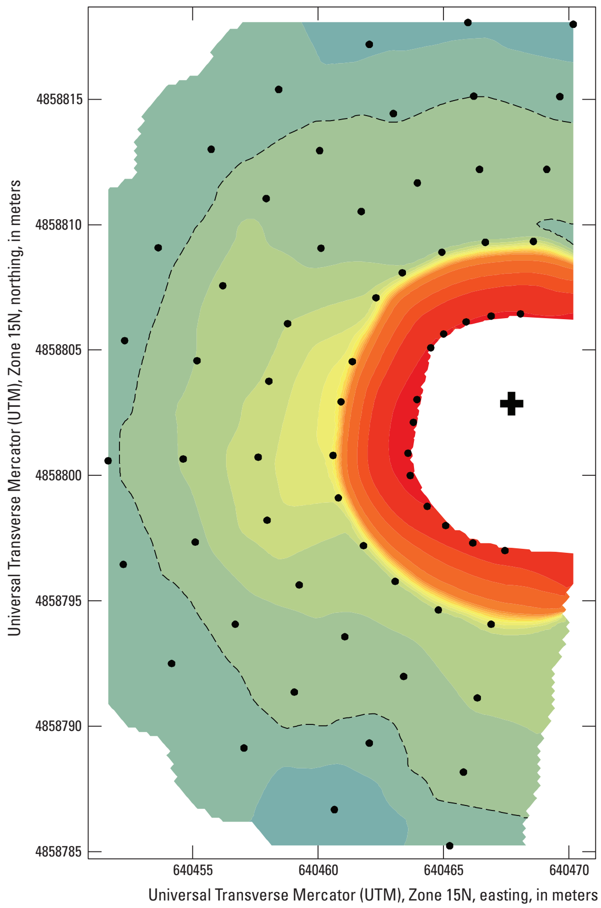
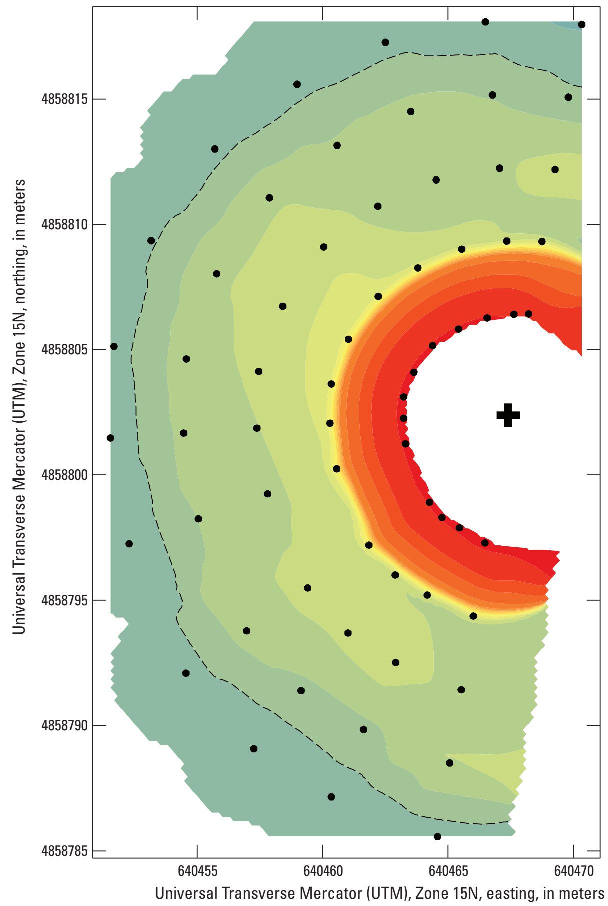
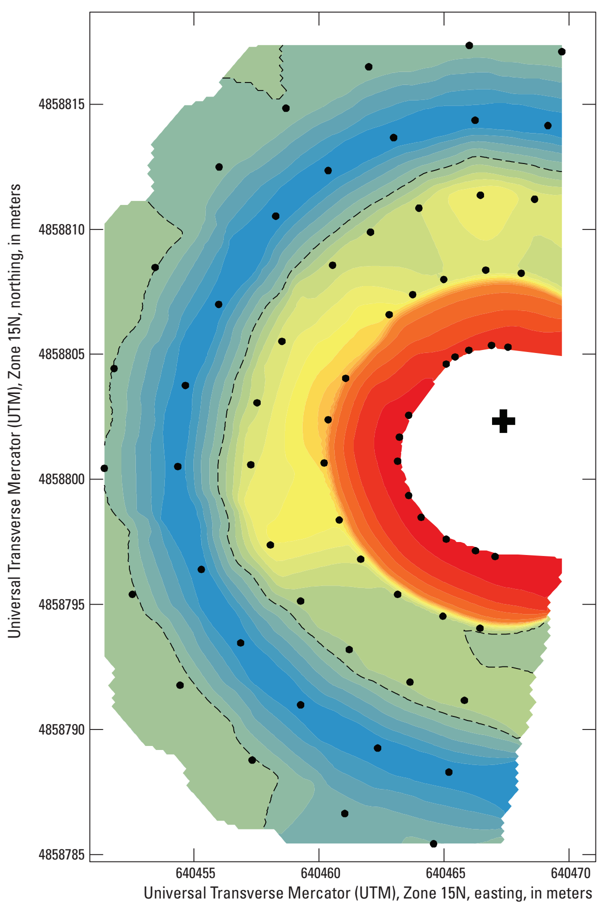


Figure 18. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 6 feet.

The difference in input air pressure did not result in large variations among the three trials. The radial extent of the 5-lb/in^2 target level at the depth of the firing ports (the 5-ft BWS maps) differs by less than 5 ft among the three trials. Similar comparisons of the 1-ft BWS and 6-ft BWS maps show similar results. The increase in input air pressure results in higher pressure gradients closer to the gun, especially comparing the 1,000-lb/in^2 trial and 1,500-lb/in^2 trial, but the overall performance of the three trials was very similar. The effect of the boundary conditions on these results may be significant. Although the pond bottom slopes very shallowly, there is an overall change in total depth of about 1 ft from the north end to the south end of the testing pond. This depth change combined with the heterogeneous nature of the southern end of the pond (transition to concrete filling and holding structures, additional pipes and filling apparatus, integrated hydrophones and tagging antennas, and so forth) seems to have an effect on the shape of the pressure field.







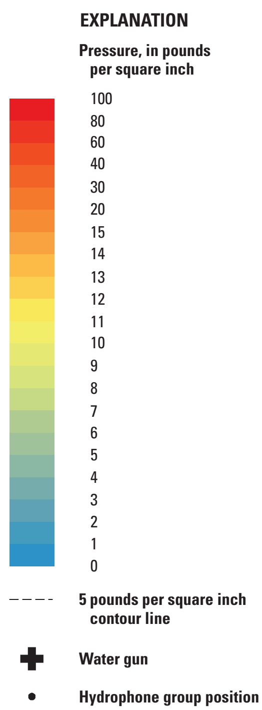


Figure 19 (top left). Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 5 feet.

Figure 20 (top right). Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 5 feet.

Figure 21 (bottom left). Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 5 feet.

Trial 3, the vertical gun scenario at 1,300 lb/in^2, was evaluated in the field. The results differed in respect to the other trials both in radial extent of the 5-lb/in^2 target value and absolute magnitude of the pressure gradient. When compared to trial 1, the absolute magnitude of the pressure values showed a decrease of about 30 percent despite firing at a higher pressure. Owing to the poor performance of the water gun in this orientation and the difficulty of securing the water gun in this position for operational testing, this trial was not investigated further.

Experimental Barrier Assessment Scenario

Four hydrophone groups were positioned on the PVC boom, which was centered between the two guns. The hydrophones were deployed at depths of 1.5, 3.5, and 5.5 ft BWS. The initial separation between the water guns was 99 ft. The distance was then increased gradually from 99 ft to 120 ft in 5-ft nominal increments.

After testing at 99, 104.5, 109.5, 115, and 120 ft of separation between the water guns, it was determined that only the 99-ft separation maintained sufficient pressure across the distance between the two water guns to meet the 5-lb/in^2 target value. The barriers that were generated in all of the iterations confirmed results from previous scenarios in the Morris 2013 study. Gaps—areas with pressures less than the 5-lb/in^2 target value—opened first at the upper, 1.5-ft hydrophone group. Gaps were the narrowest at the depths closest to the firing ports. Gaps on the 5.5-ft group of hydrophones opened at wider distances than the 1.5-ft group and remained narrower overall. The effect of the boundary conditions on these results may be significant, however. The magnitude of the pressure field and, therefore, the potential effectiveness as a barrier could be either constrained or enhanced depending on the water depth at which the water guns are deployed.

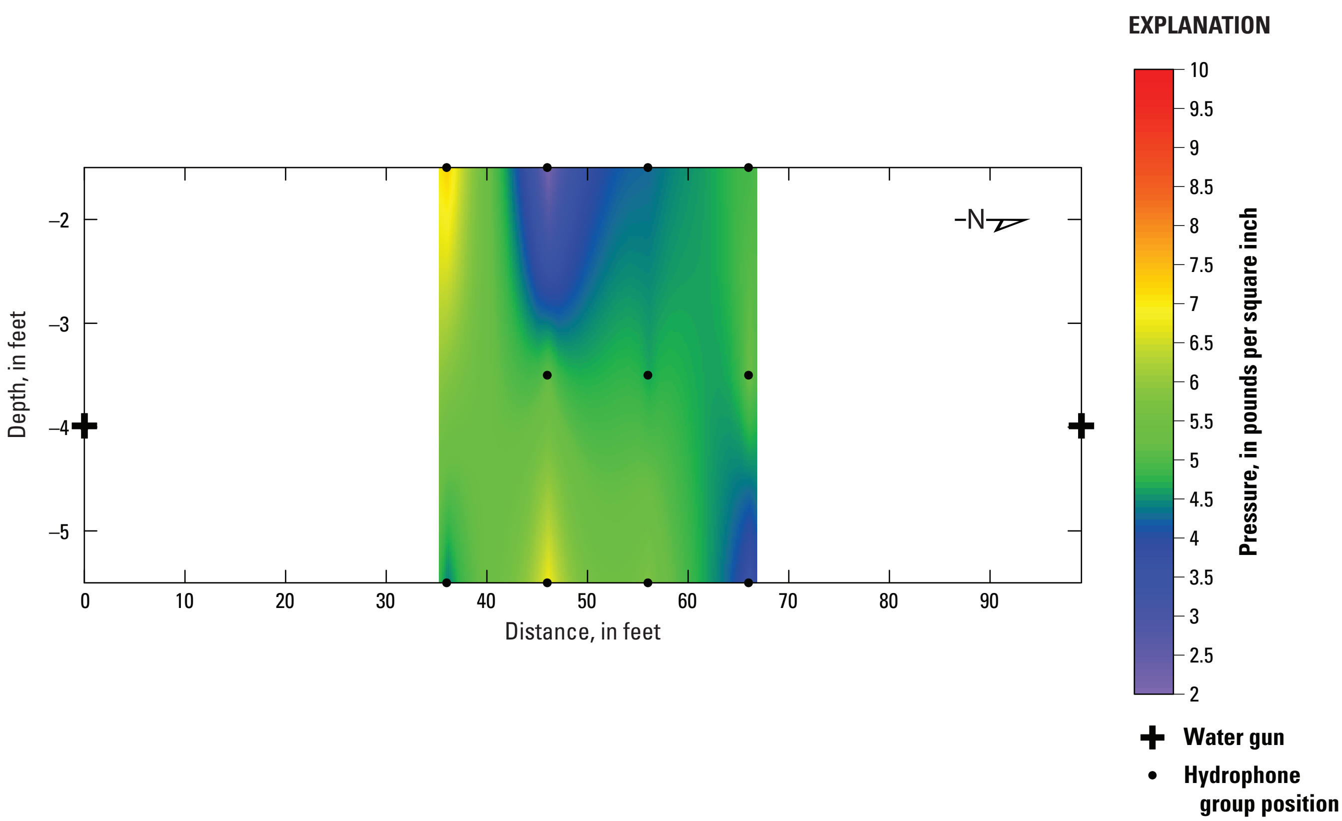


Figure 22. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 99 feet.

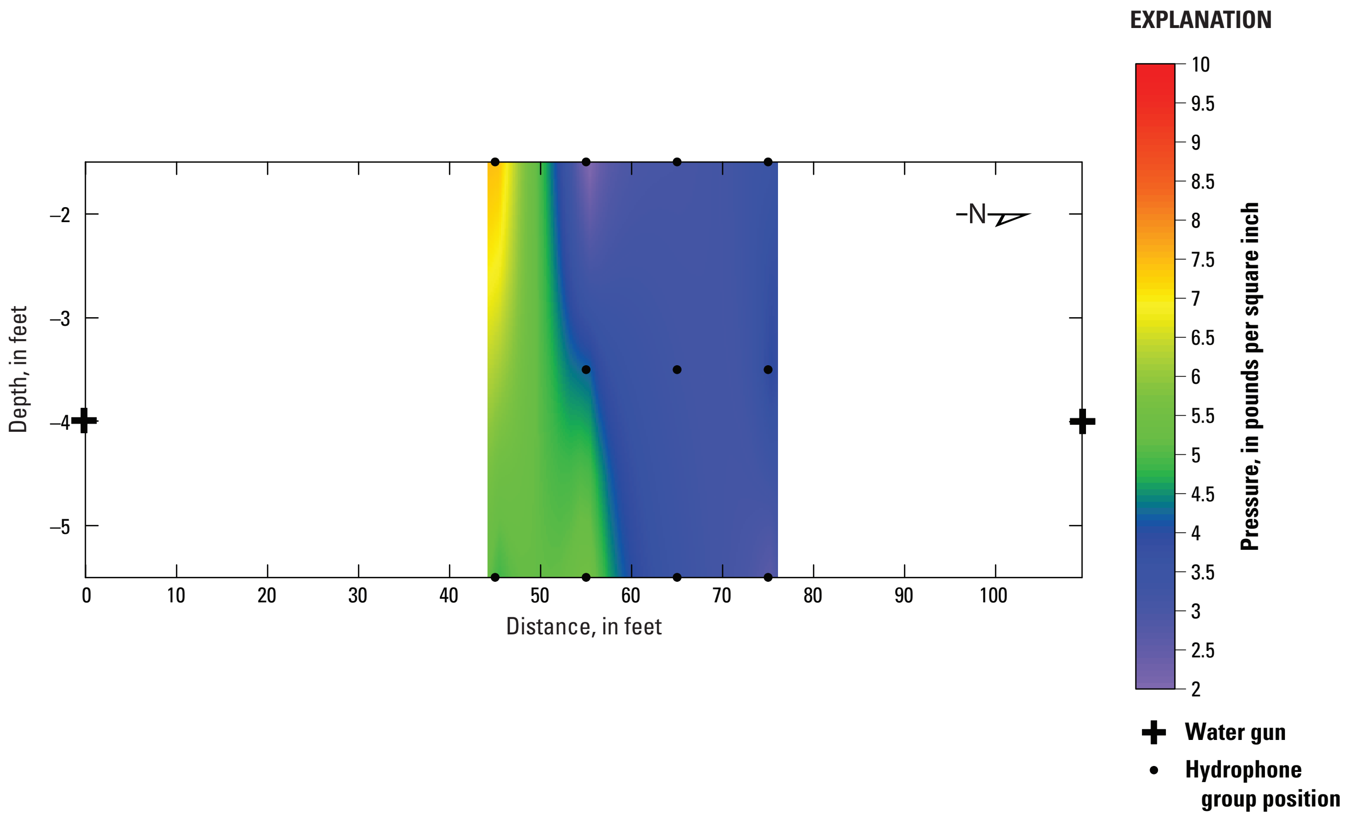


Figure 23. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 120 feet.

Summary

Two studies, one each in September 2012 and July 2013, were performed to evaluate the physical characteristics of the pressure field created by a water gun fired in a shallow, confined environment. Pressure was evaluated by using blast-rated hydrophones and underwater blast sensors.

The purpose of the September 2012 study was to collect data from the pressure field created by a 1-in^3 water gun and an 80-in^3 water gun. The 1-in^3 gun produces a horizontally omnidirectional and vertically planar pressure wave dispersal pattern that displays sharply reduced pressure above and below the plane of the gun ports. The magnitude of the pressure field produced by the 1-in^3 gun proved insufficient to be solely capable of producing a consistent target 5-lb/in^2 threshold. The 80-in^3 gun produces an omnidirectional pressure field with a maximum extent of 45 ft for the 5-lb/in^2 target values. Absolute pressure values increased with increasing depth, but the size of the 5-lb/in^2 target area decreased with depth.

The July 2013 study further defined and increased the resolution of data collected in the 2012 study to evaluate the effectiveness of the 80-in^3 water gun(s) in a barrier context relative to a 5-lb/in^2 target value. Three scenarios were tested: fish behavior, single gun assessment, and experimental barrier assessment. The fish behavior scenario provided pressure mapping that simulated the area and conditions of previous fish behavior studies within the same testing pond, as well as an improved understanding of the interaction of two water guns. The single gun assessment scenario replicated the 80-in^3 gun scenario from the 2012 study but with higher data density on both the horizontal and vertical planes. This scenario confirmed many of the results of the 80-in^3 gun study in 2012; in particular, pressure increase with depth and the absence of directionality of the water beyond 10 ft. These data are affected by the boundary conditions of the test pond. Variations from established pressure relative to depth trends due to the effect of the wave front on the bottom of the pond were observed. The experimental barrier evaluation scenario results indicate that 99 ft is the maximum extent that two water guns fired at 1,500 lb/in^2 can maintain a continuous 5-lb/in^2 pressure field at the depths of the pond.

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Appendix 1.

Pressure maps produced during all experiments, in sequential order, to facilitate comparison between the different scenarios and studies.

Abbreviations used in figures: ft, feet; in^3, cubic inches; lb/in^2, pounds per square inch.

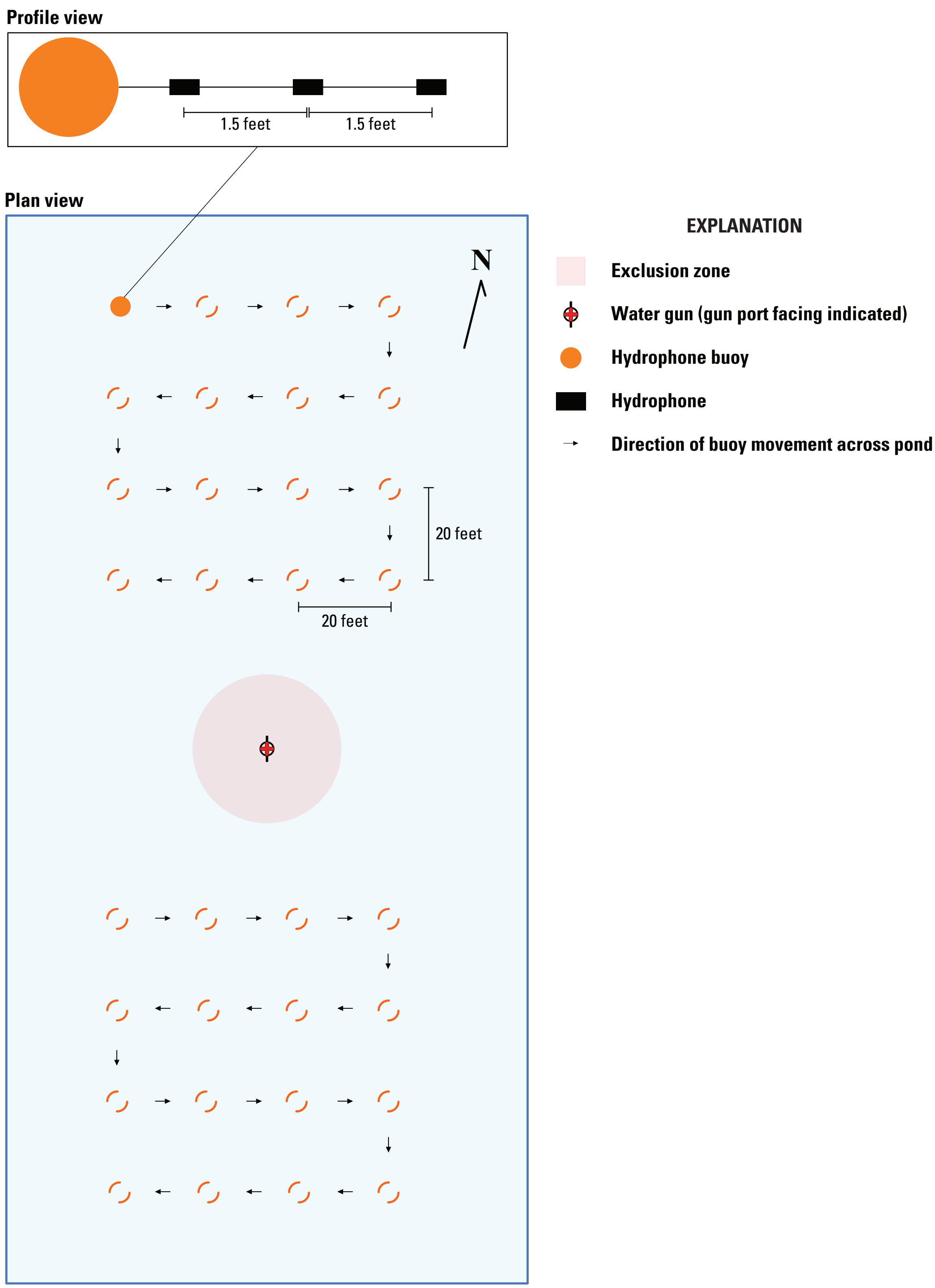

Figure 1–1. Data locations for 80-cubic-inch scenario. Red water gun indicator shows the alternate orientation of the gun ports.

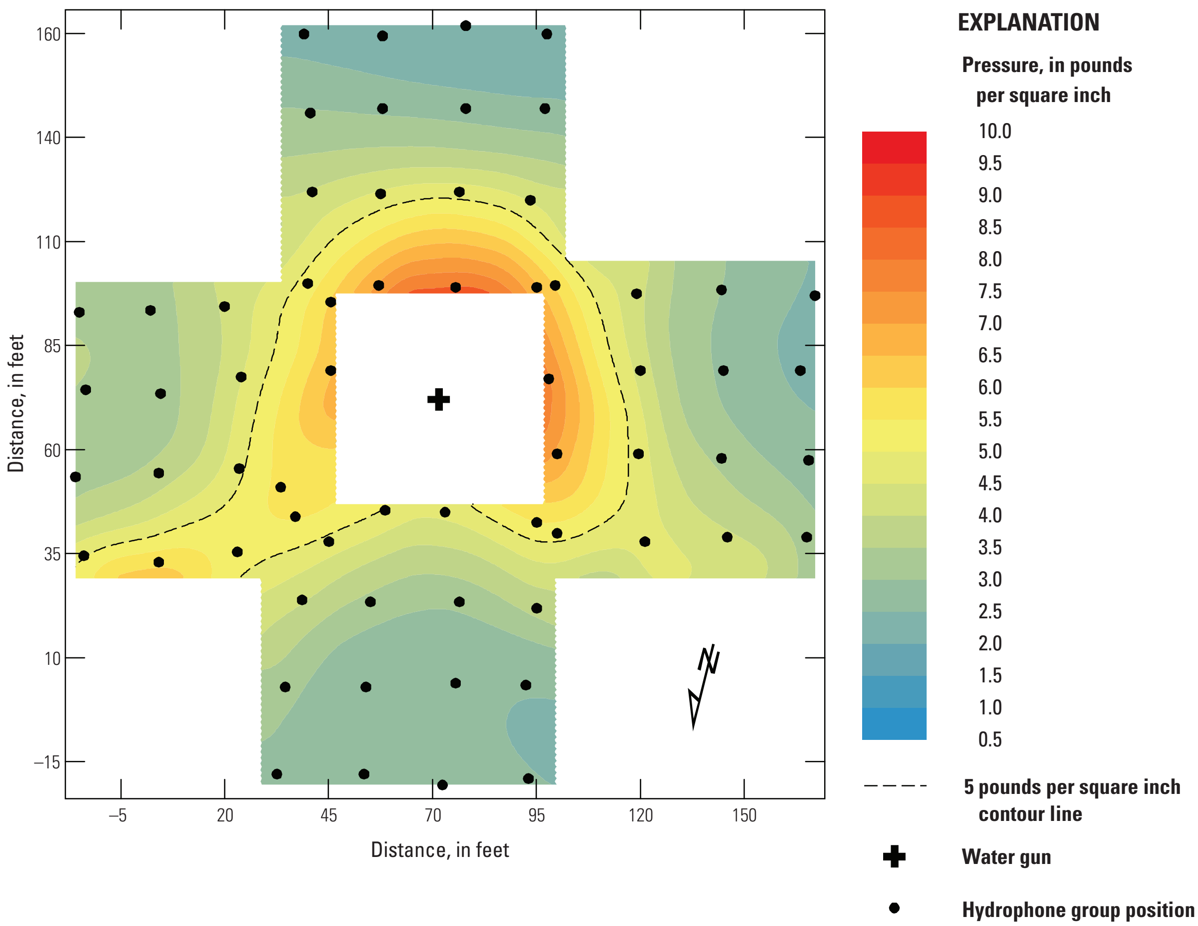

Figure 1–2. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 1.5 feet.

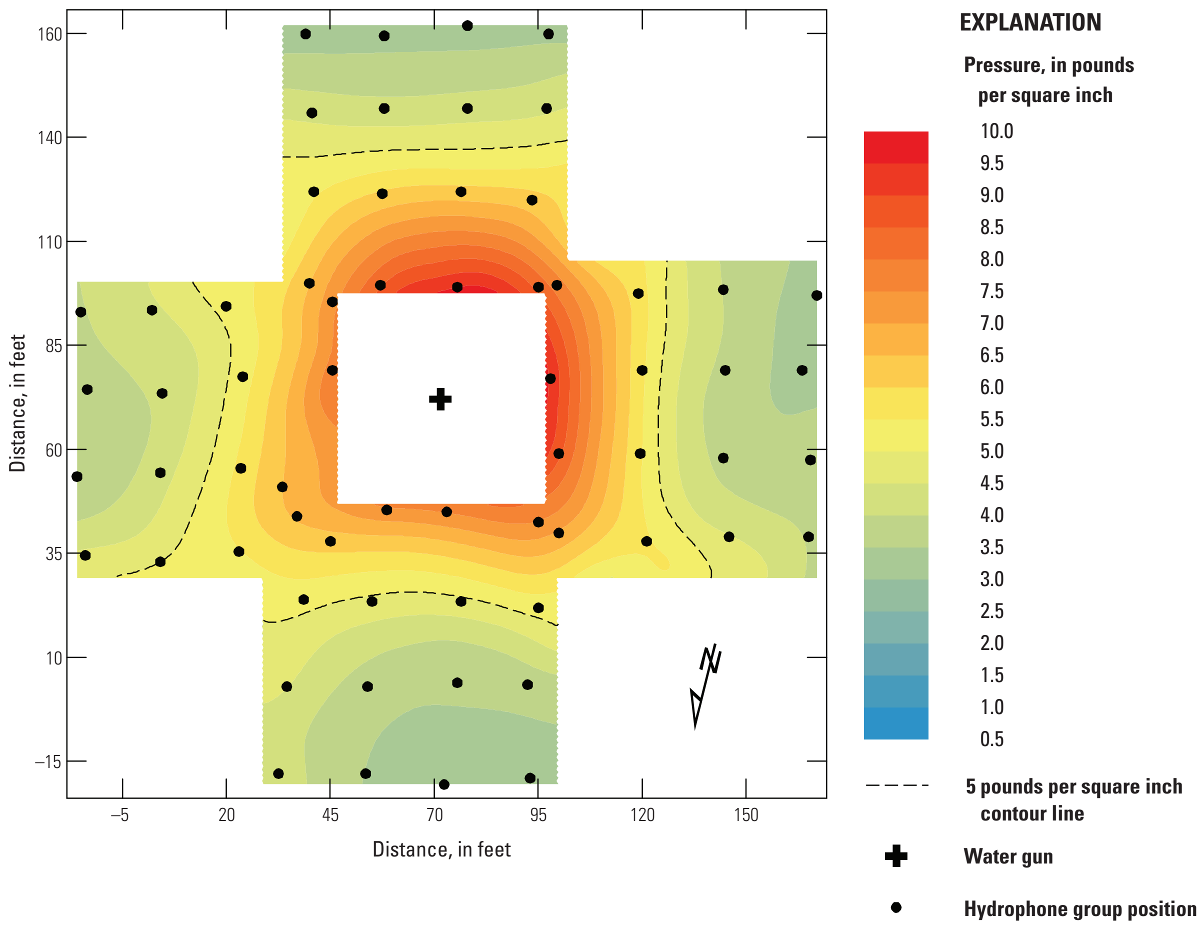

Figure 1–3. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch measurements at a depth of 3.5 feet.

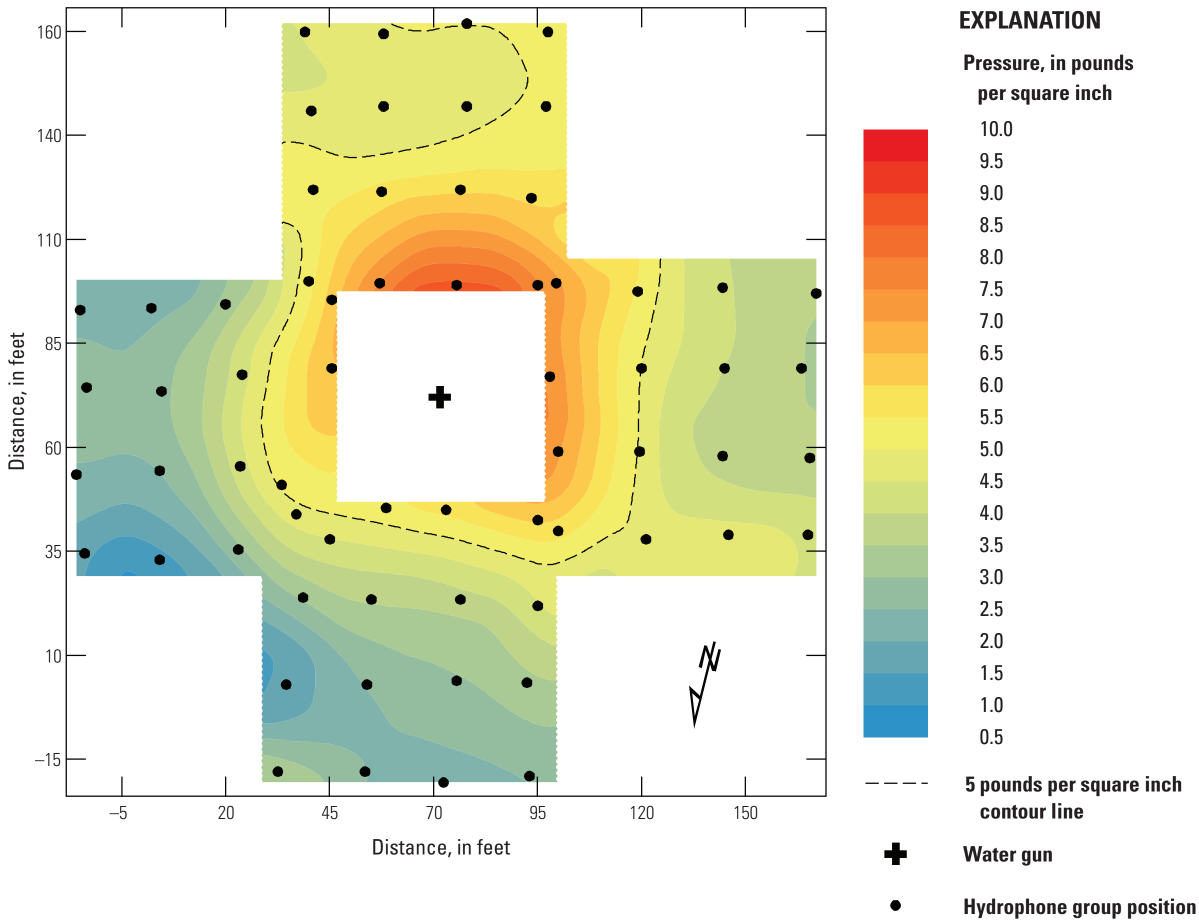

Figure 1–4. Pressure map from 80-cubic-inch water gun fired at 2,000 lpounds per square inch measurements at a depth of 5.5 feet.

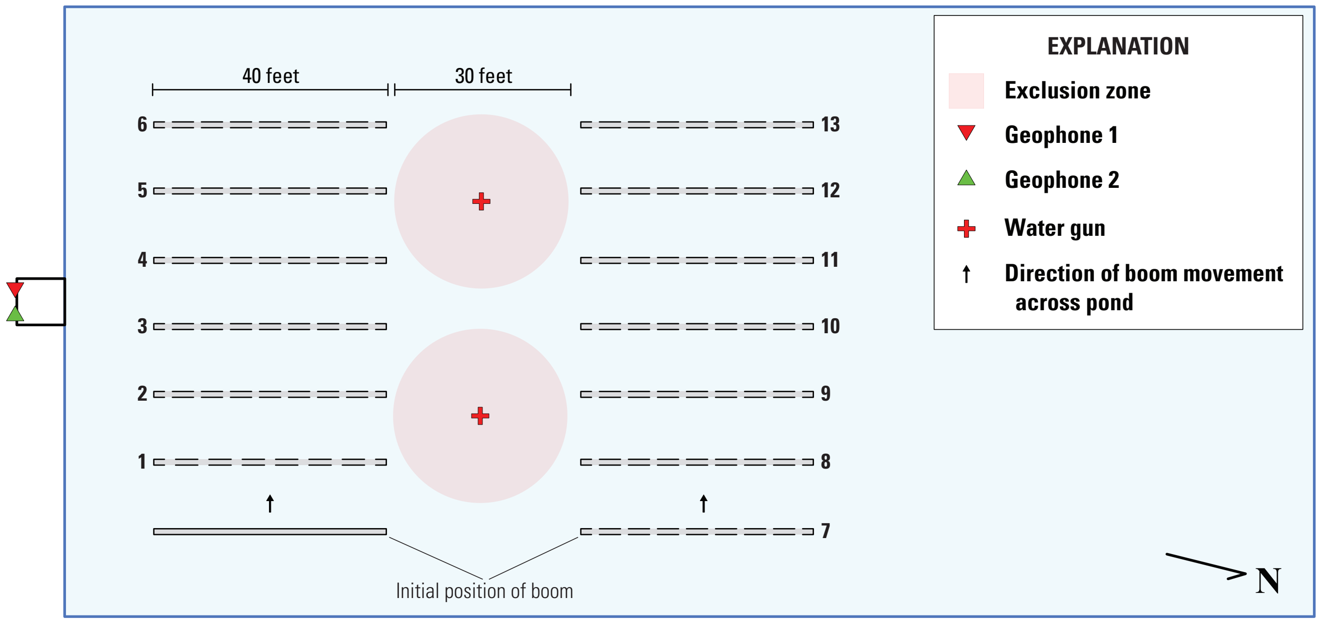

Figure 1–5. Equipment setup for the fish behavior scenario.

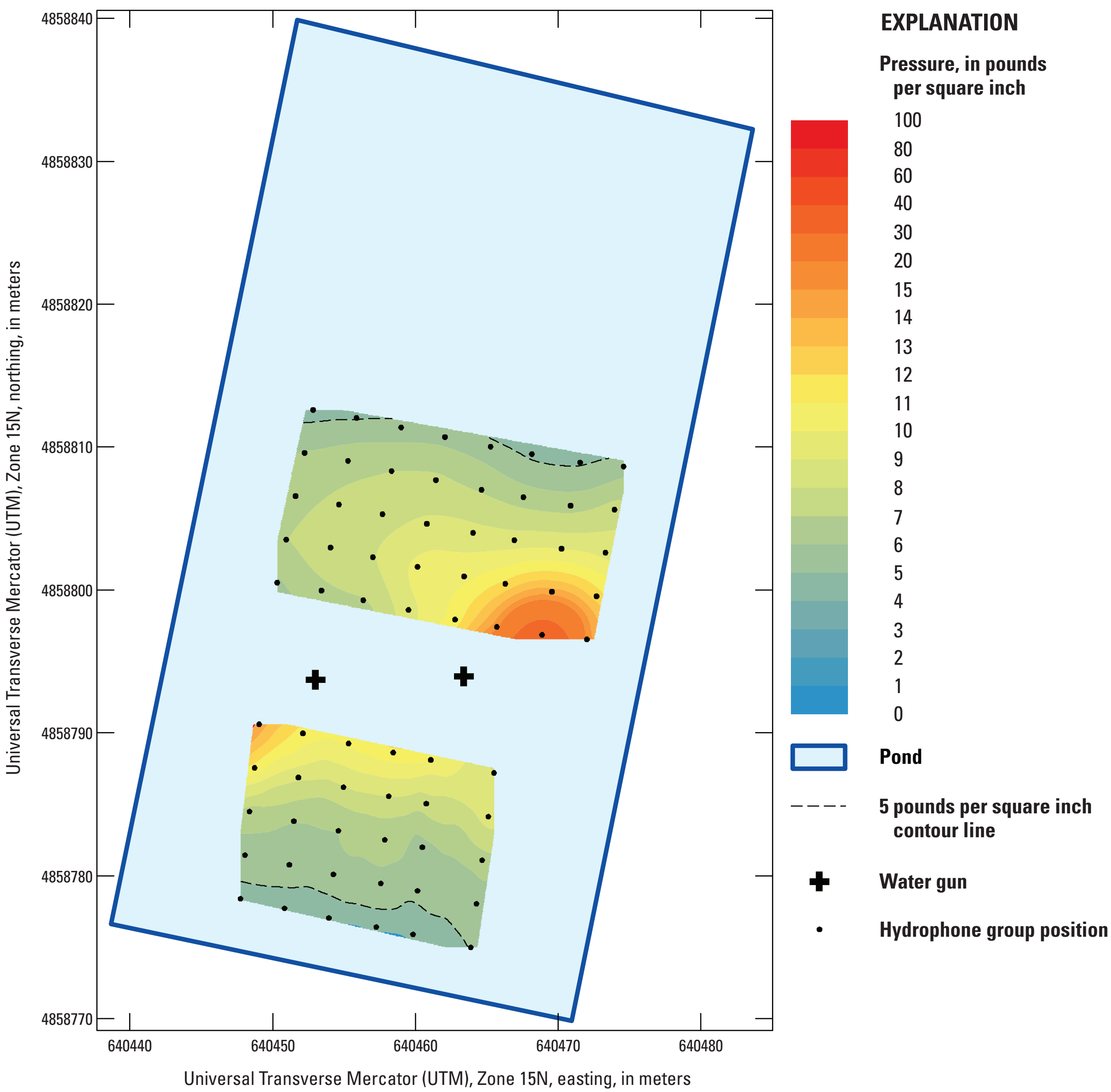

Figure 1–6. Pressure map from two 80-cubic-inch guns both fired at 1,300 pounds per square inch, measurements at a depth of 1.5 feet.

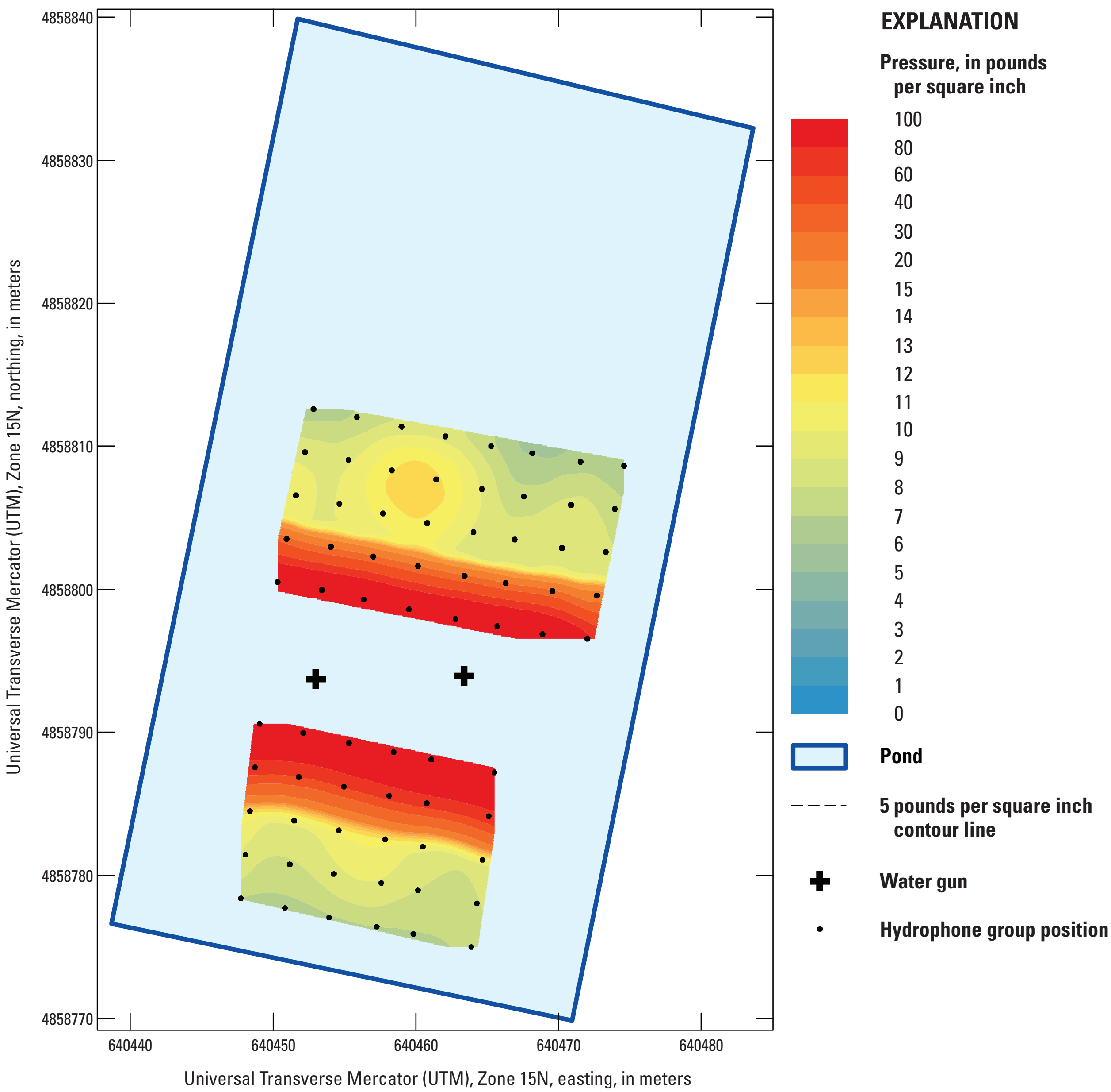

Figure 1–7. Pressure map from two 80-cubic-inchwater guns both fired at 1,300 pounds per square inch, measurements at a depth of 3.5 feet.

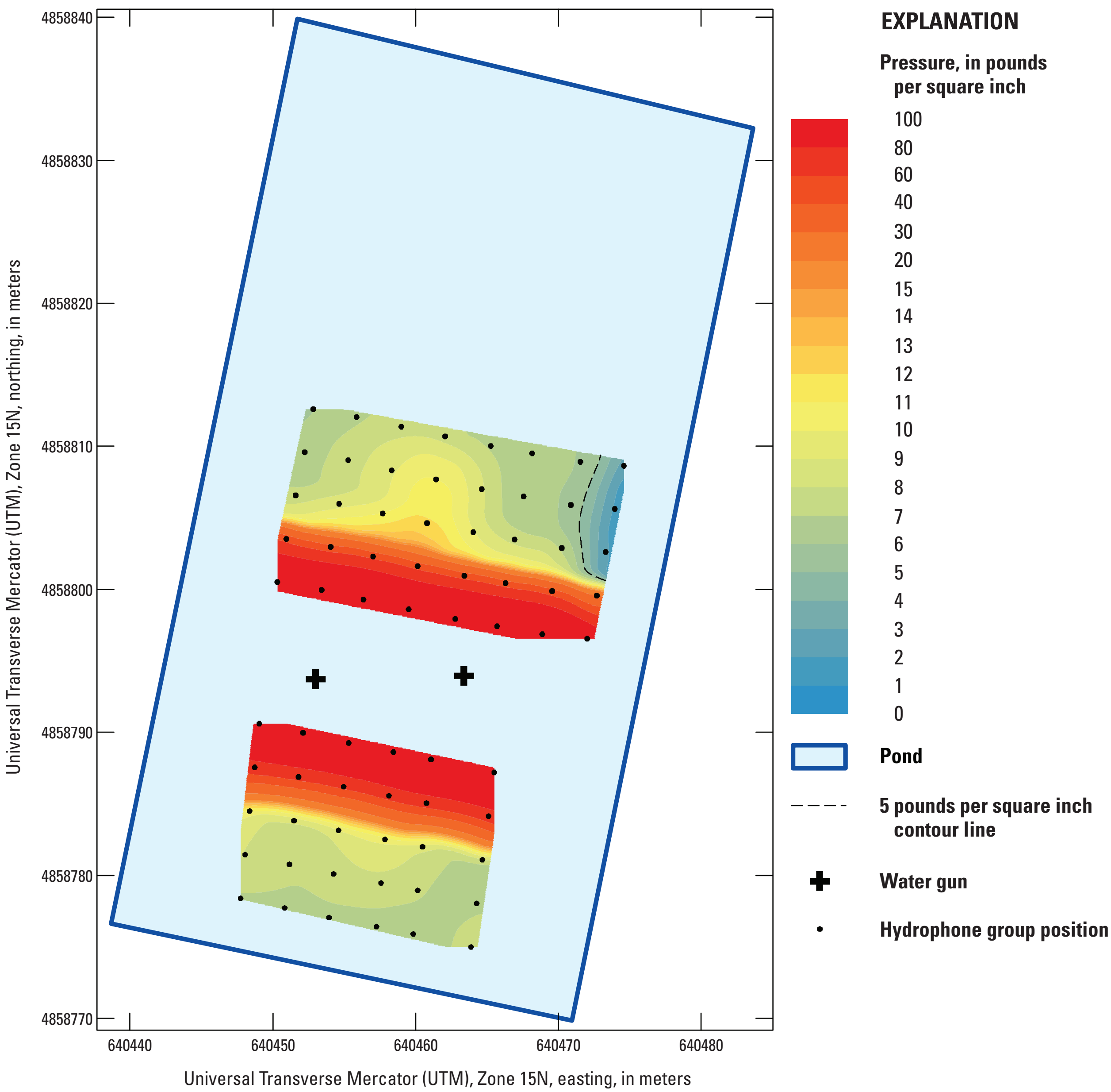

Figure 1–8. Pressure map from two 80-cubic-inch water guns both fired at 1,300 pounds per square inch, measurements at a depth of 5.5 feet.

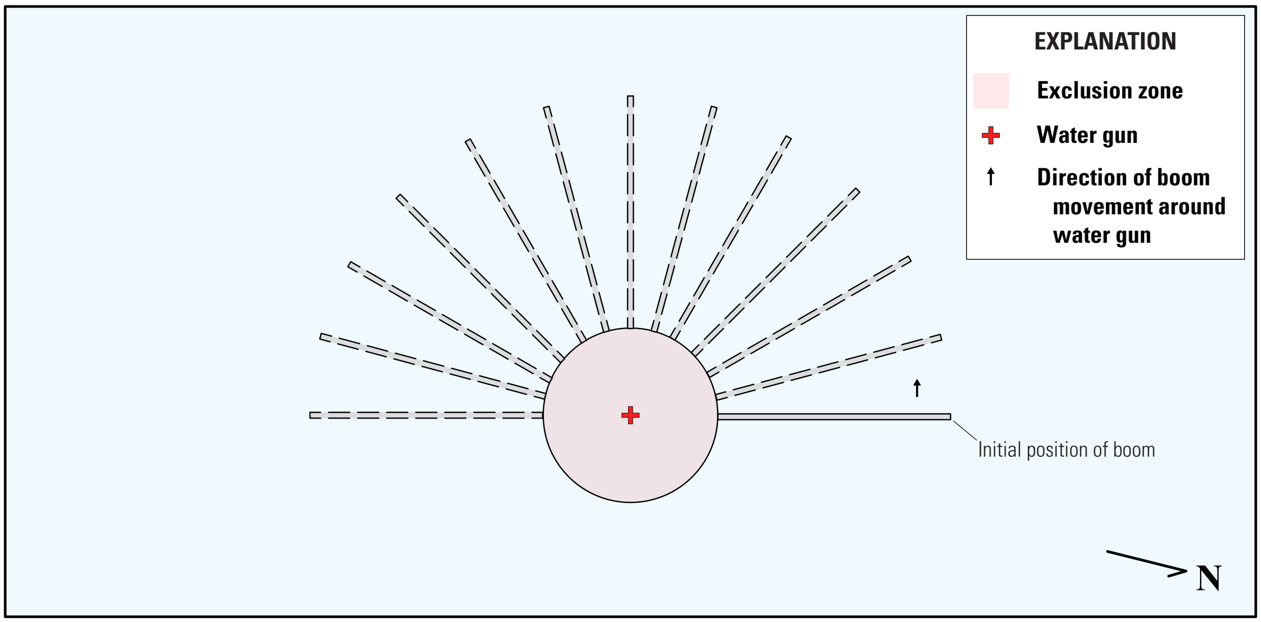

Figure 1–9. Equipment setup for the single gun assessment scenario.

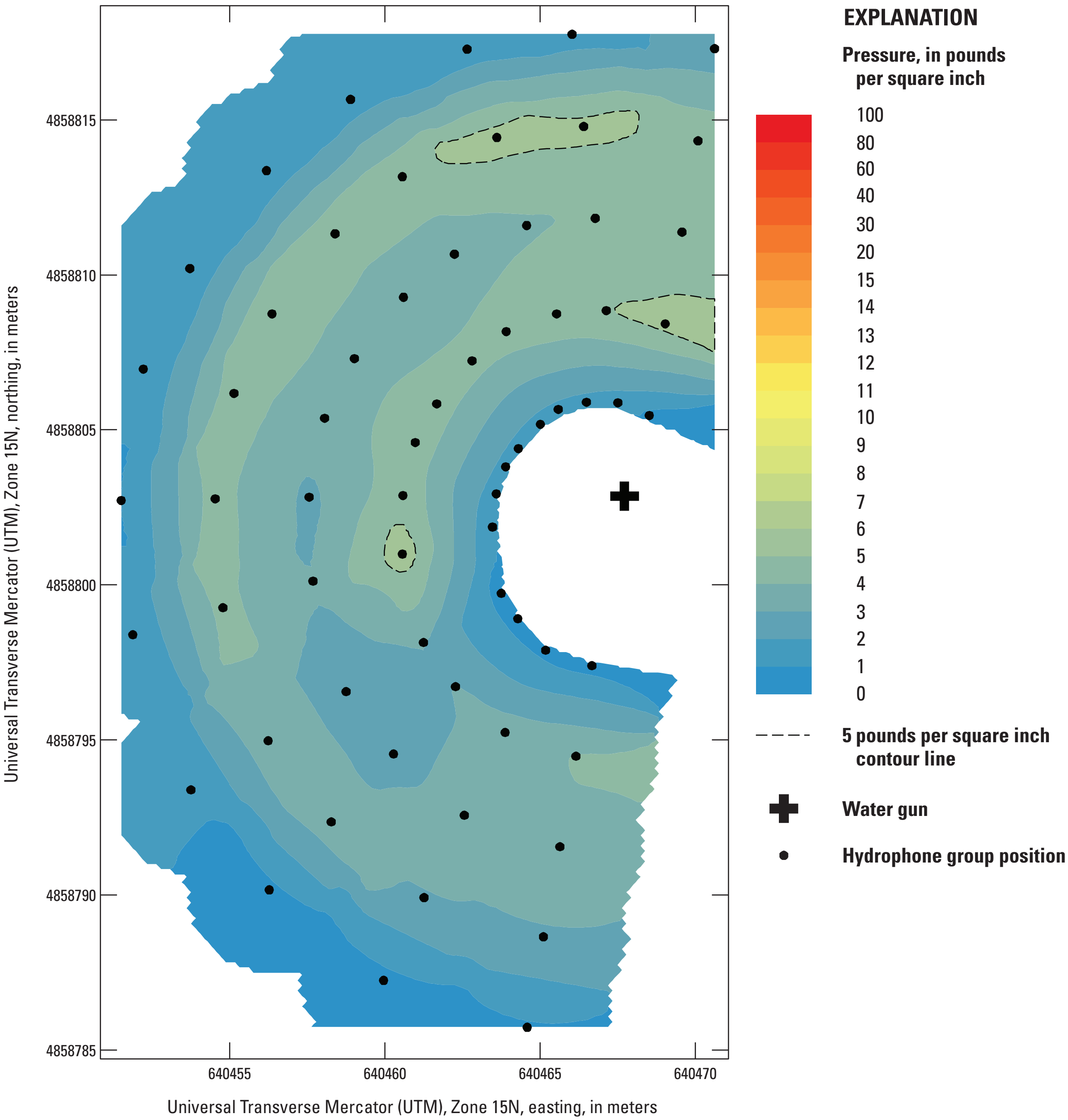

Figure 1–10. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 1 foot.

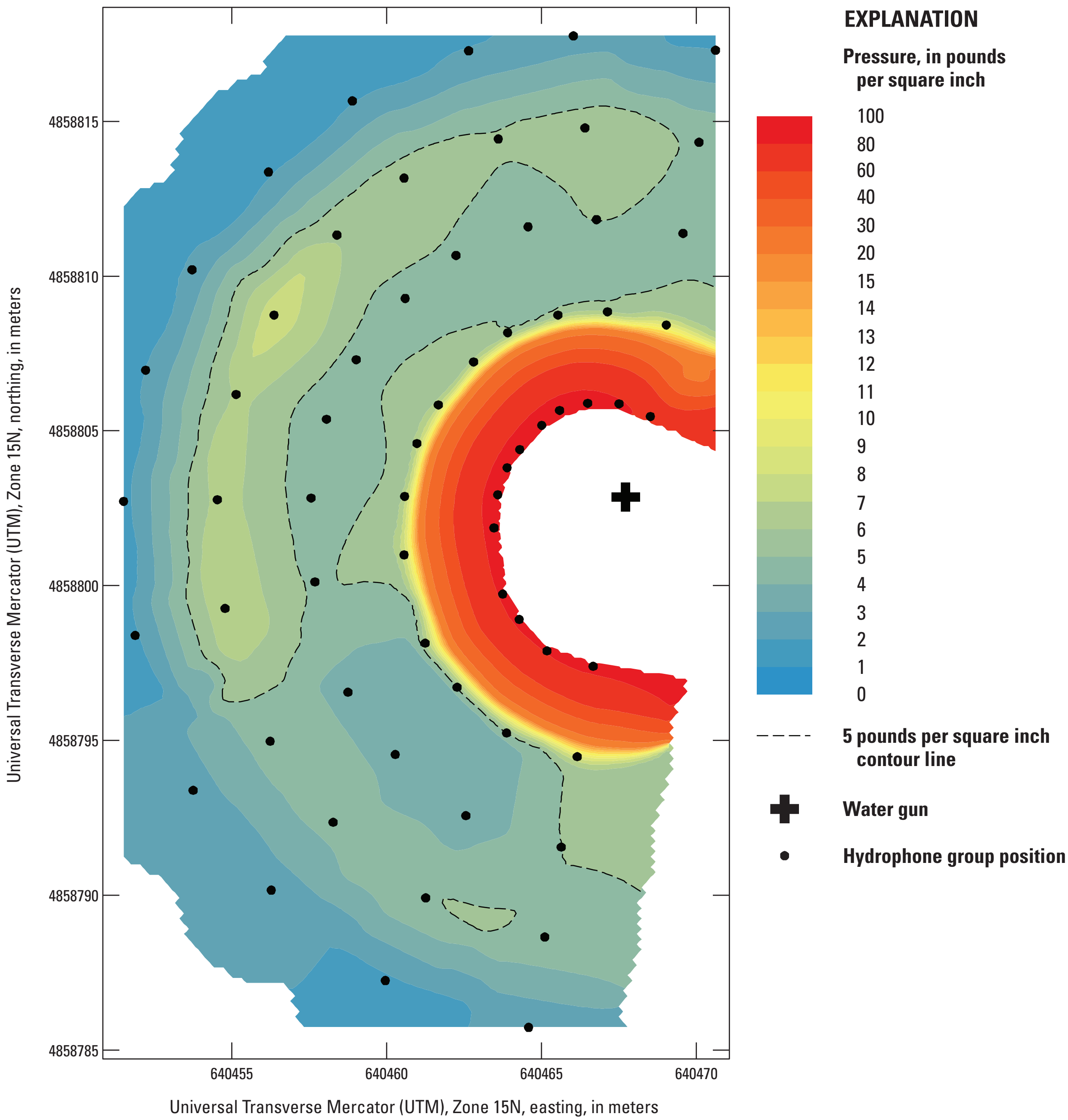

Figure 1–11. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 2 feet.

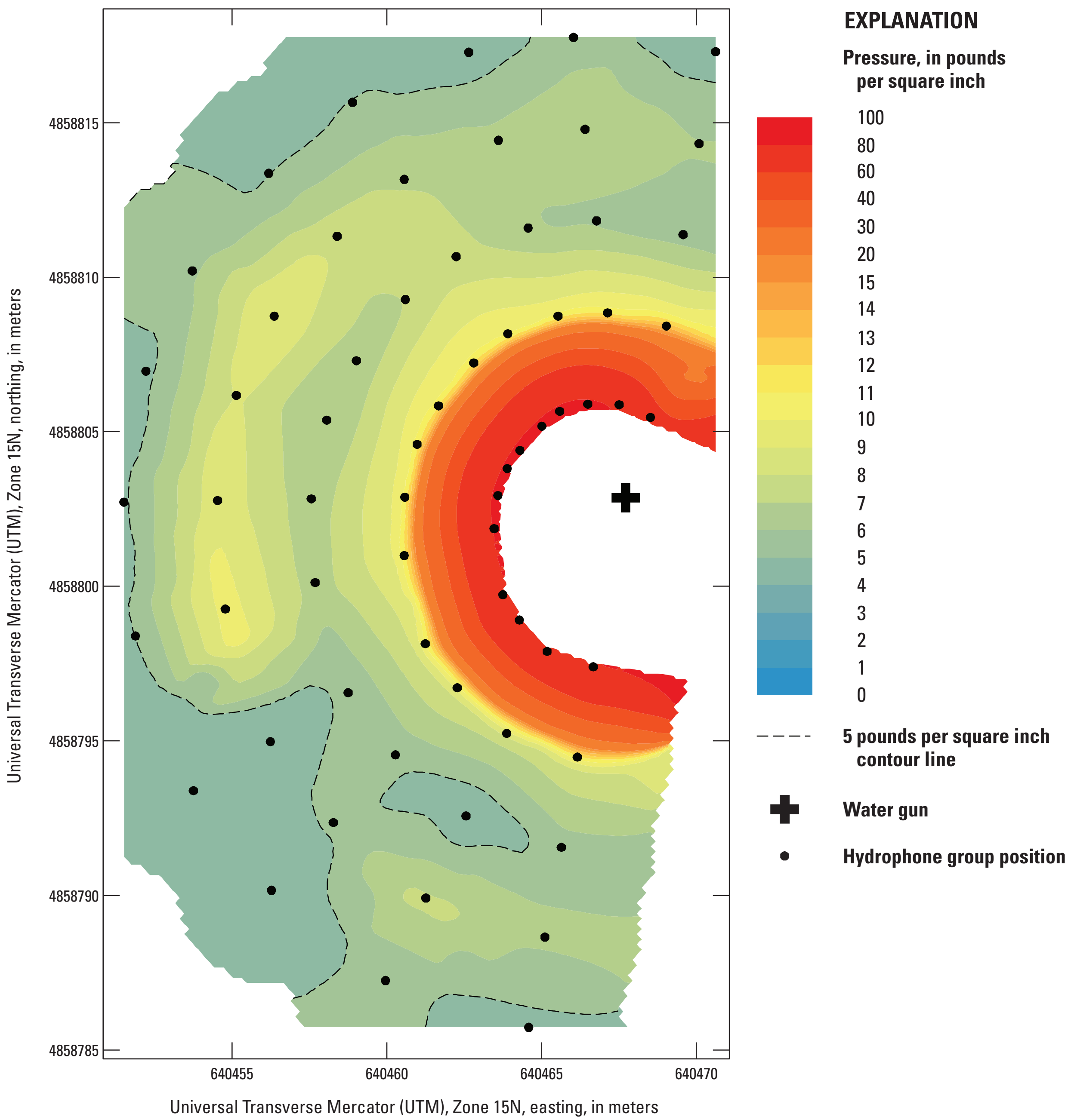

Figure 1–12. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 3 feet.

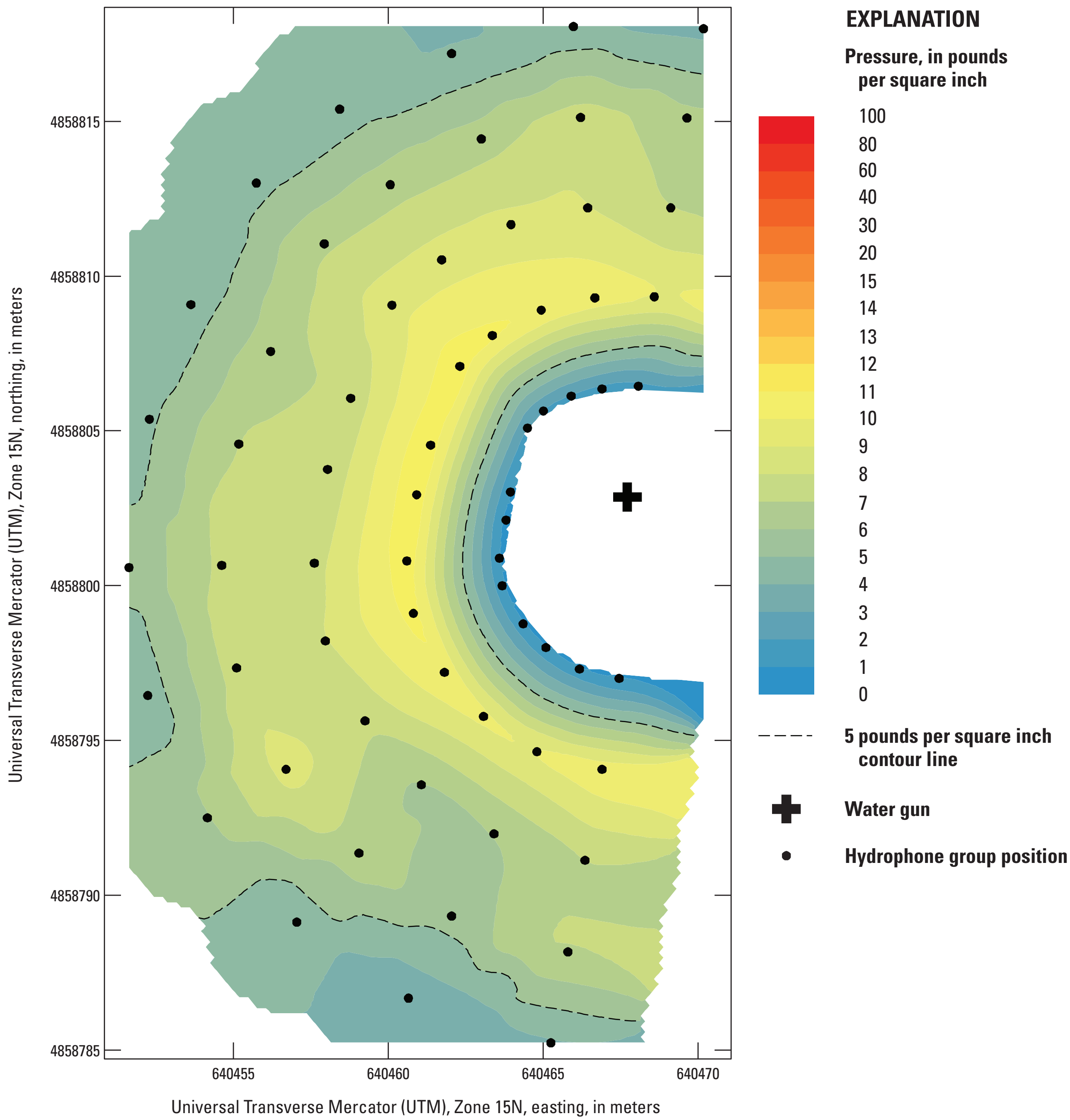

Figure 1–13. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 4 feet.

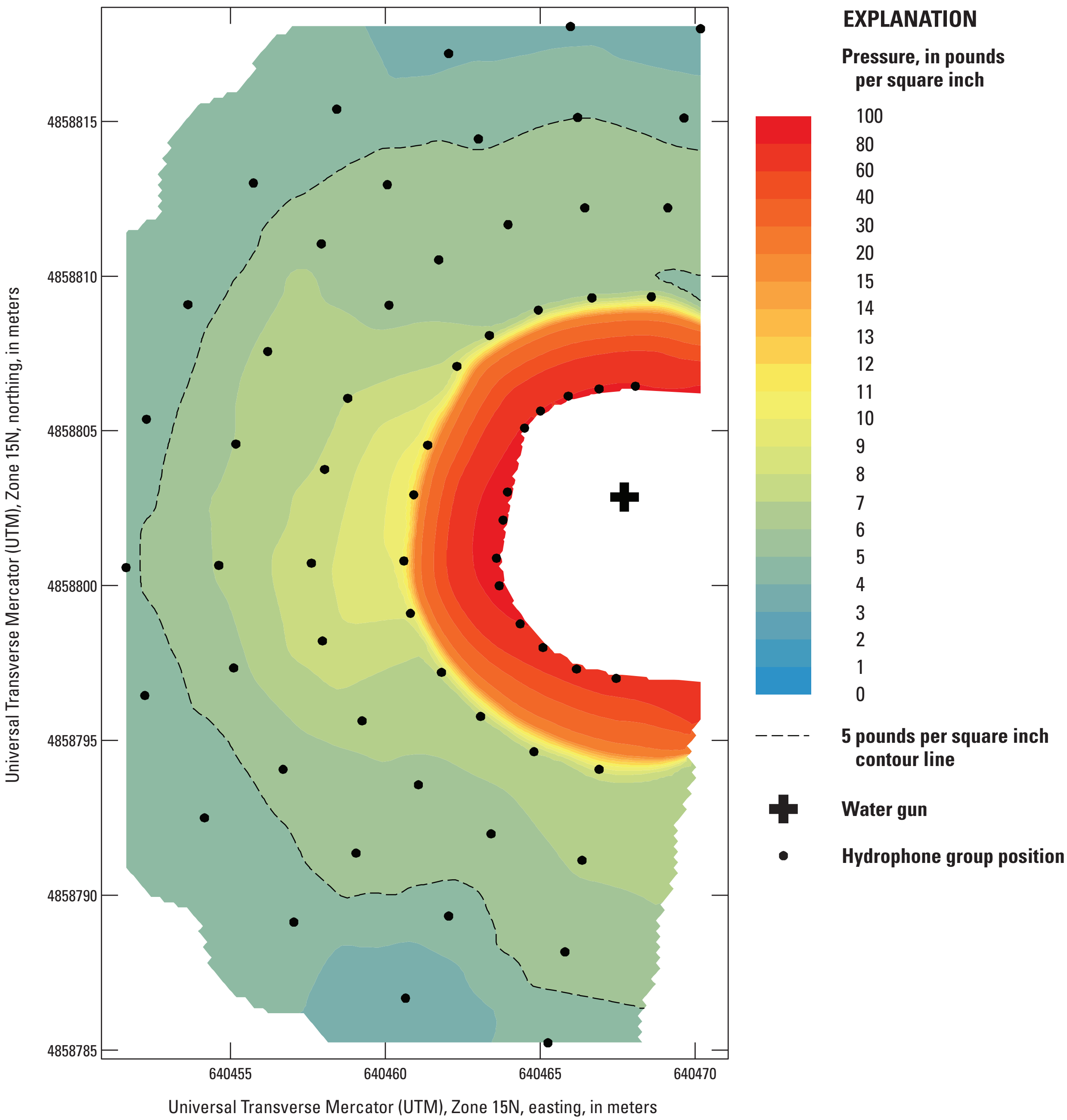

Figure 1-14. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch, measurements at a depth of 5 feet.

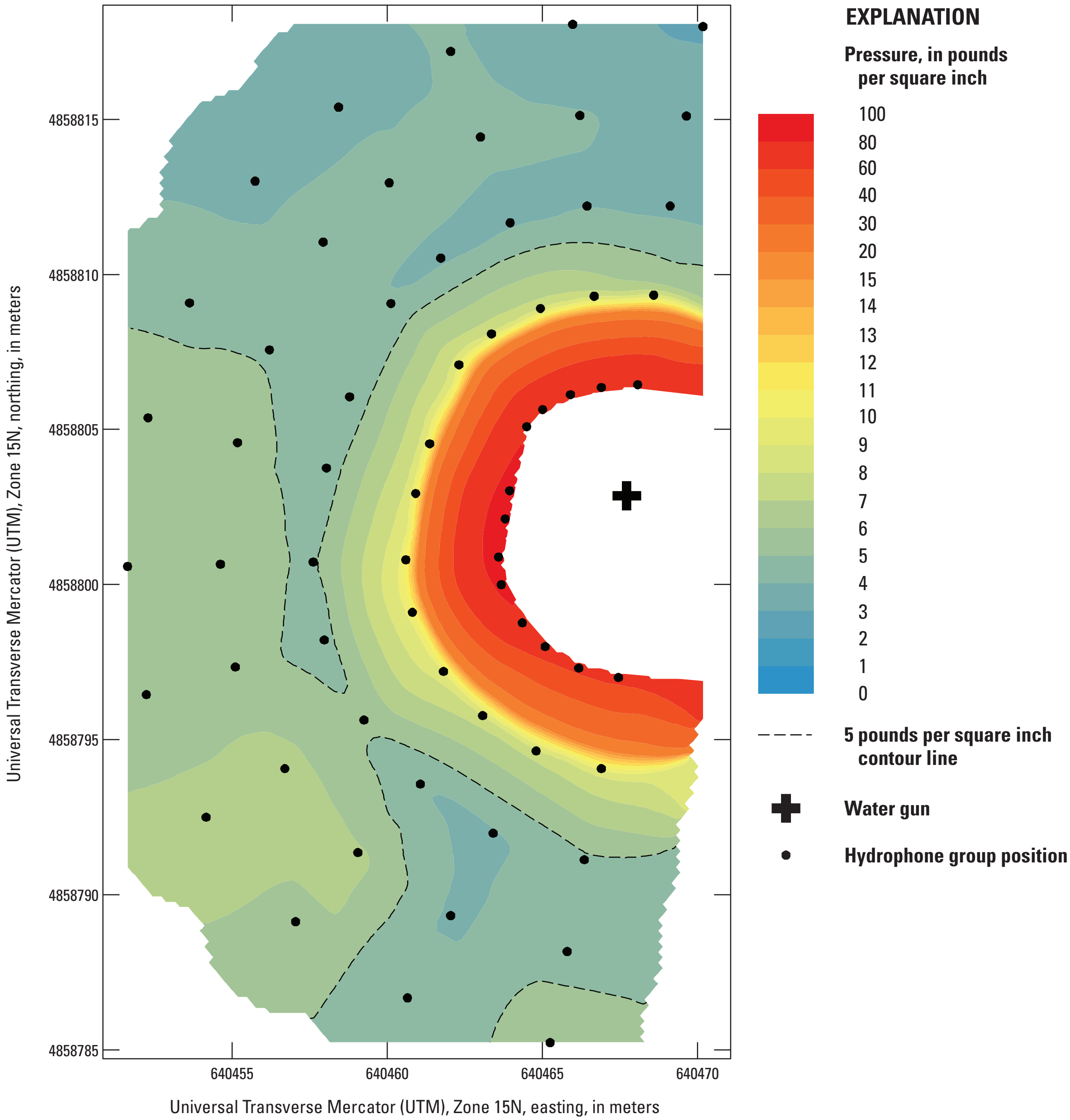

Figure 1–15. Pressure map from 80-cubic-inch water gun fired at 1,000 pounds per square inch measurements at a depth of 6 feet.

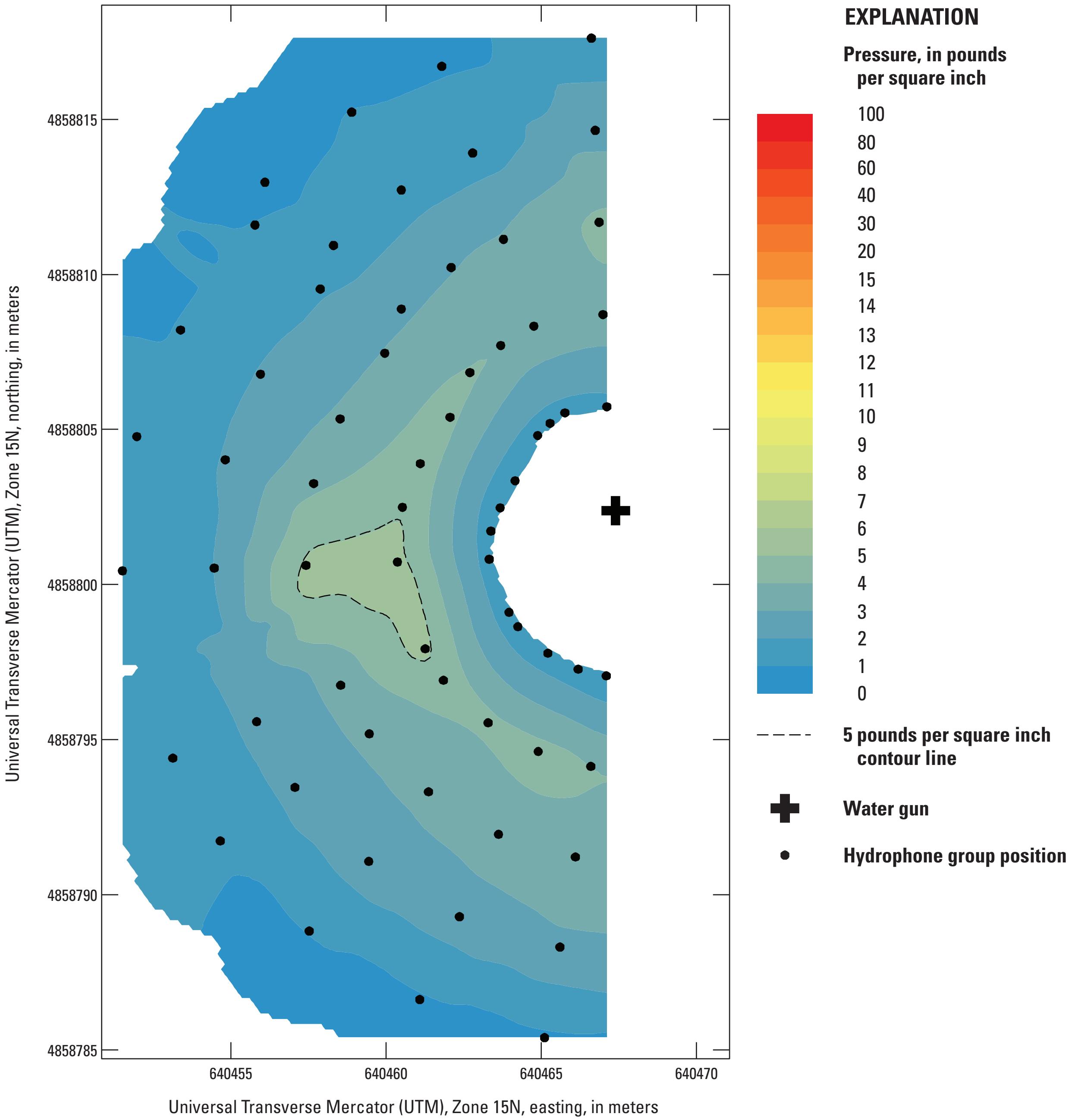

Figure 1–16. Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 1 foot.

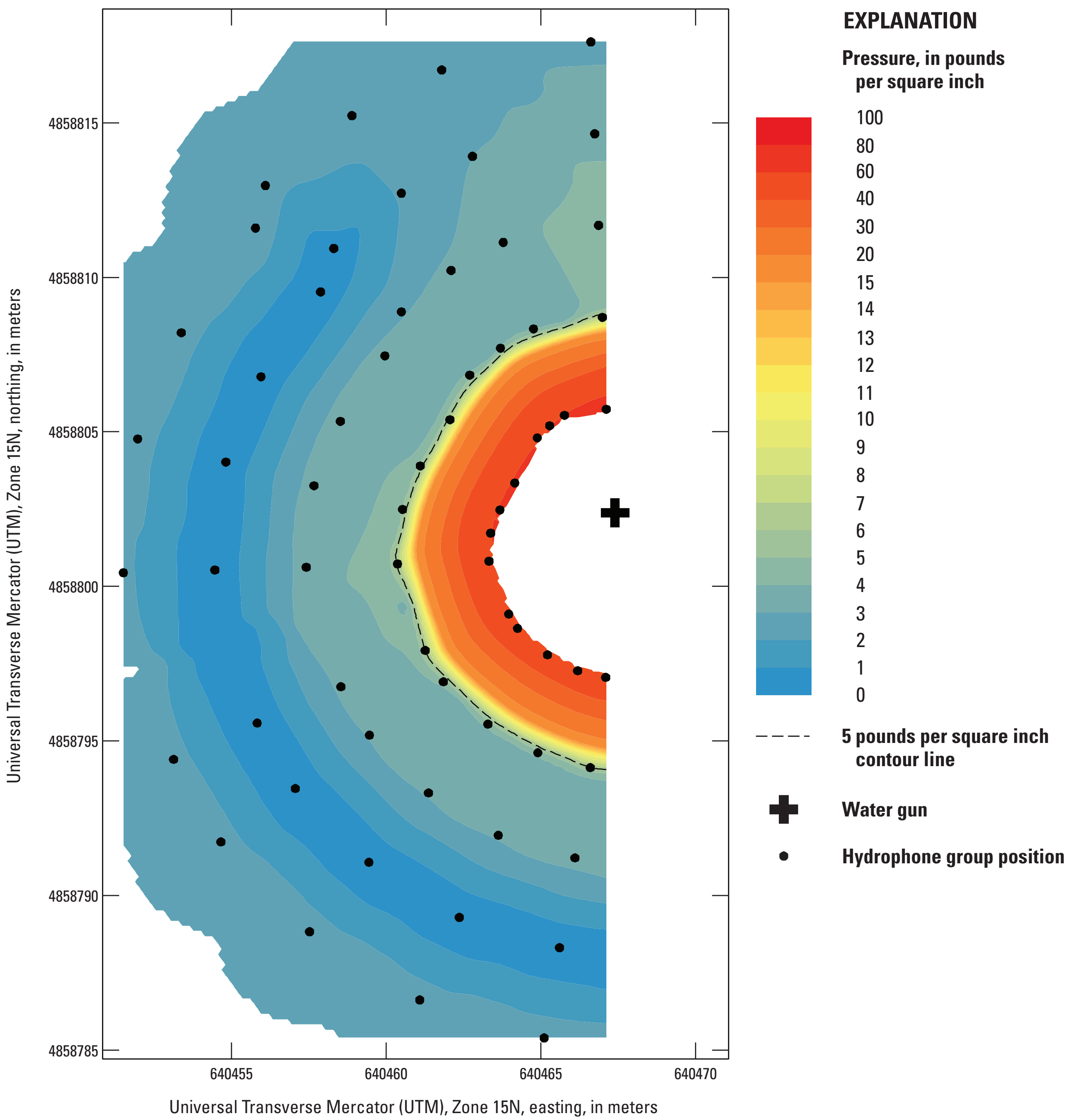

Figure 1–17. Pressure map from -cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 2 feet.

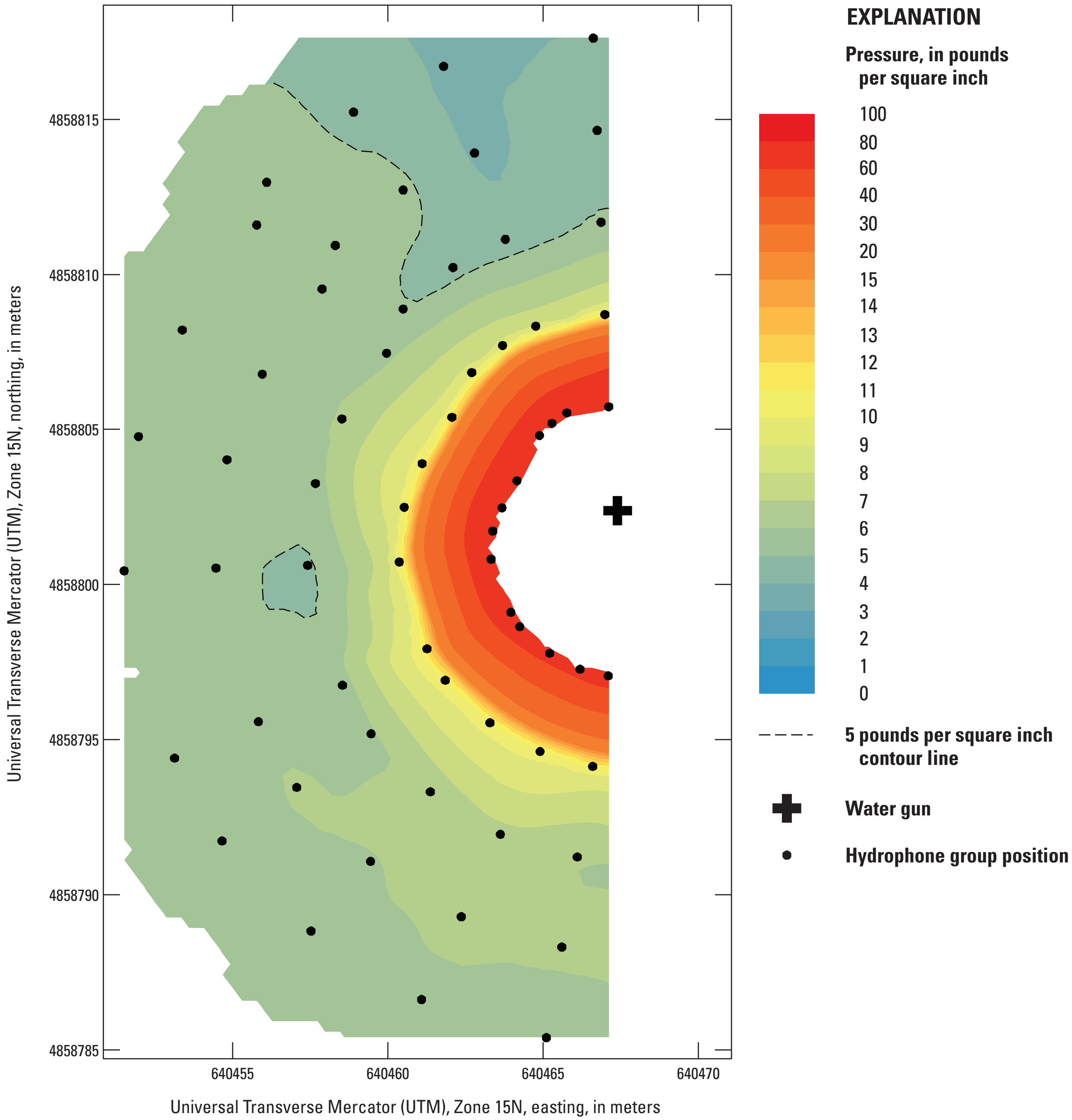

Figure 1–18. Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 3 feet.

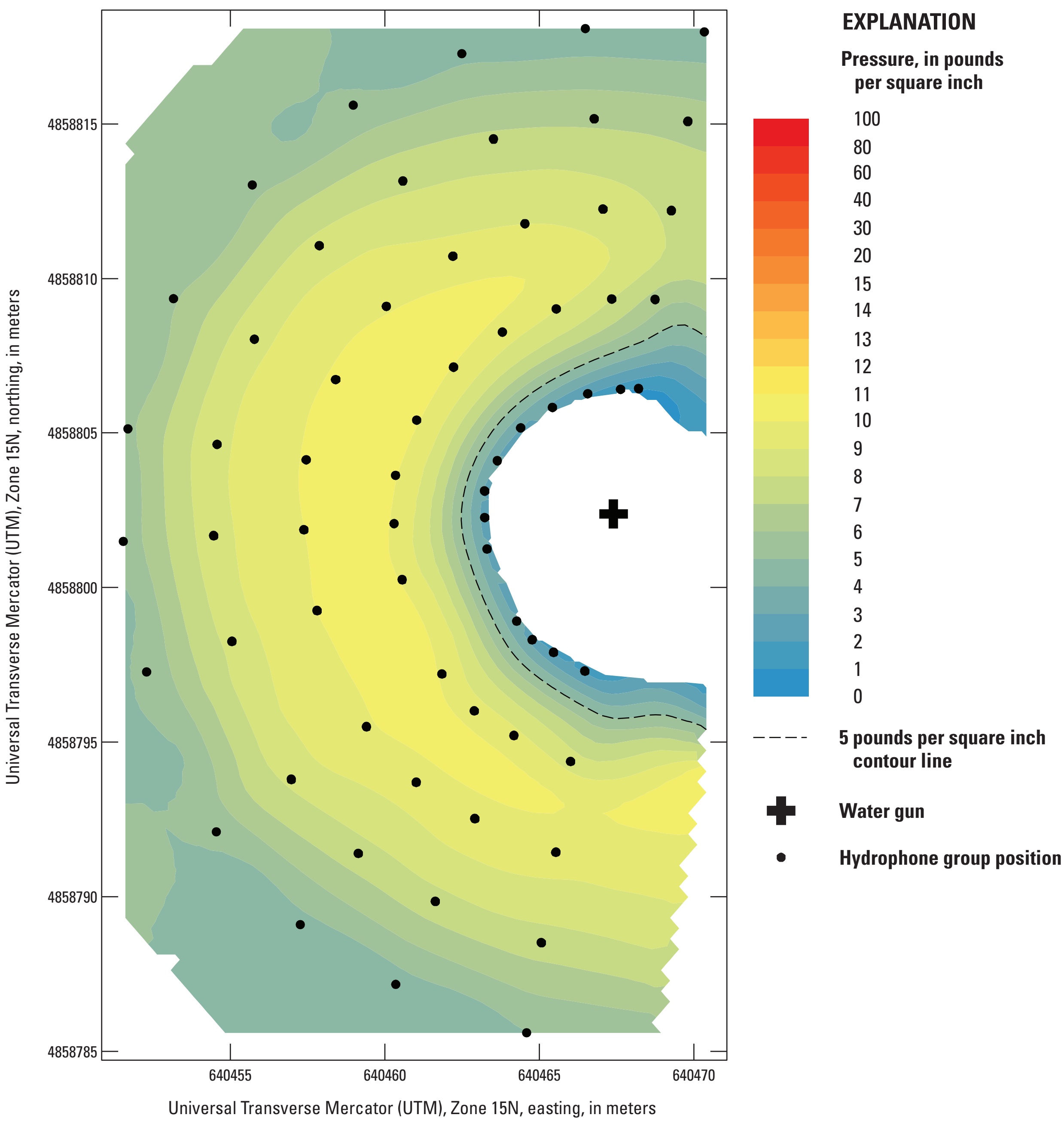

Figure 1–19. Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 4 feet.

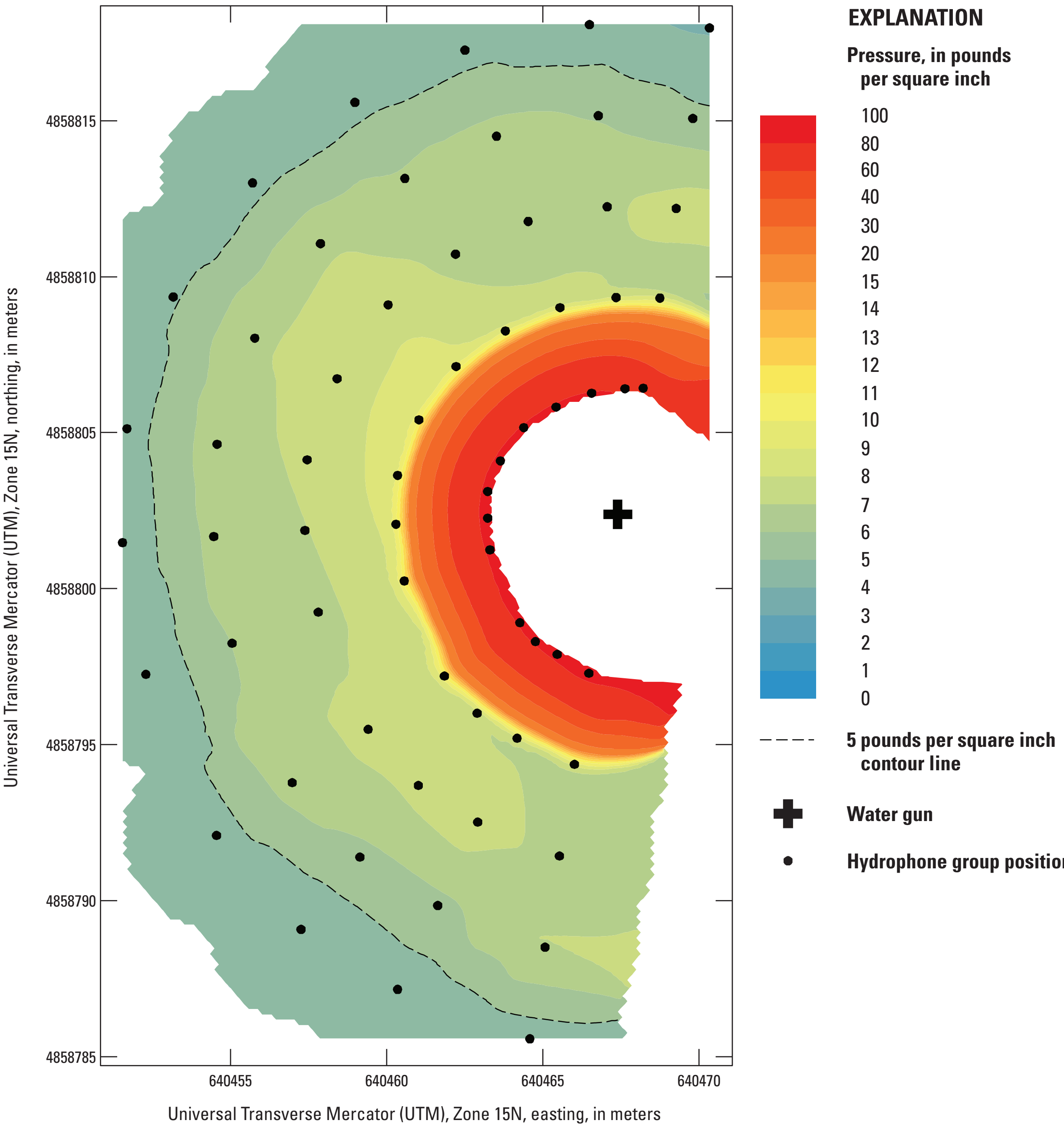

Figure 1–20. Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 5 feet.

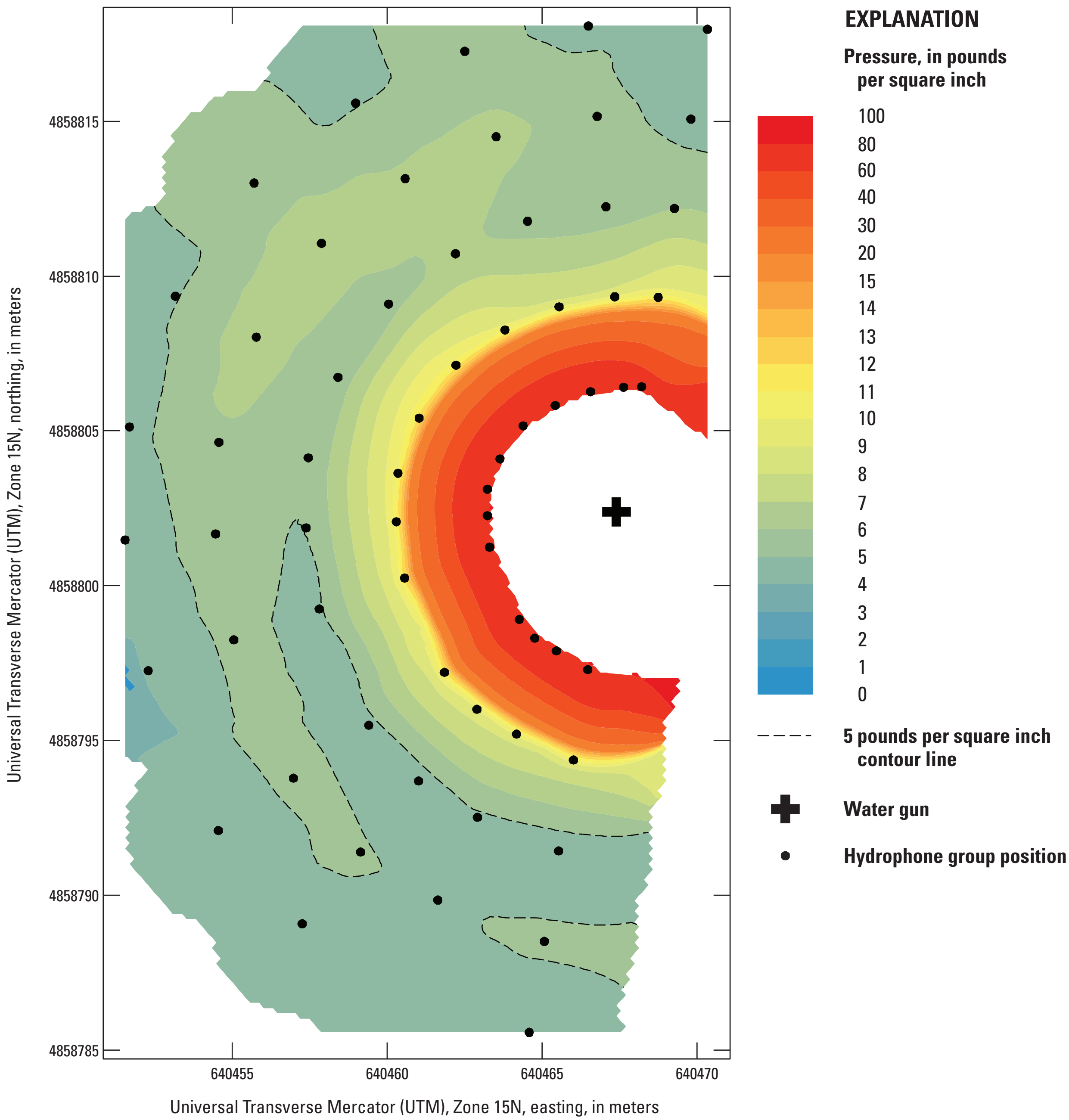

Figure 1–21. Pressure map from 80-cubic-inch water gun fired at 1,500 pounds per square inch, measurements at a depth of 6 feet.

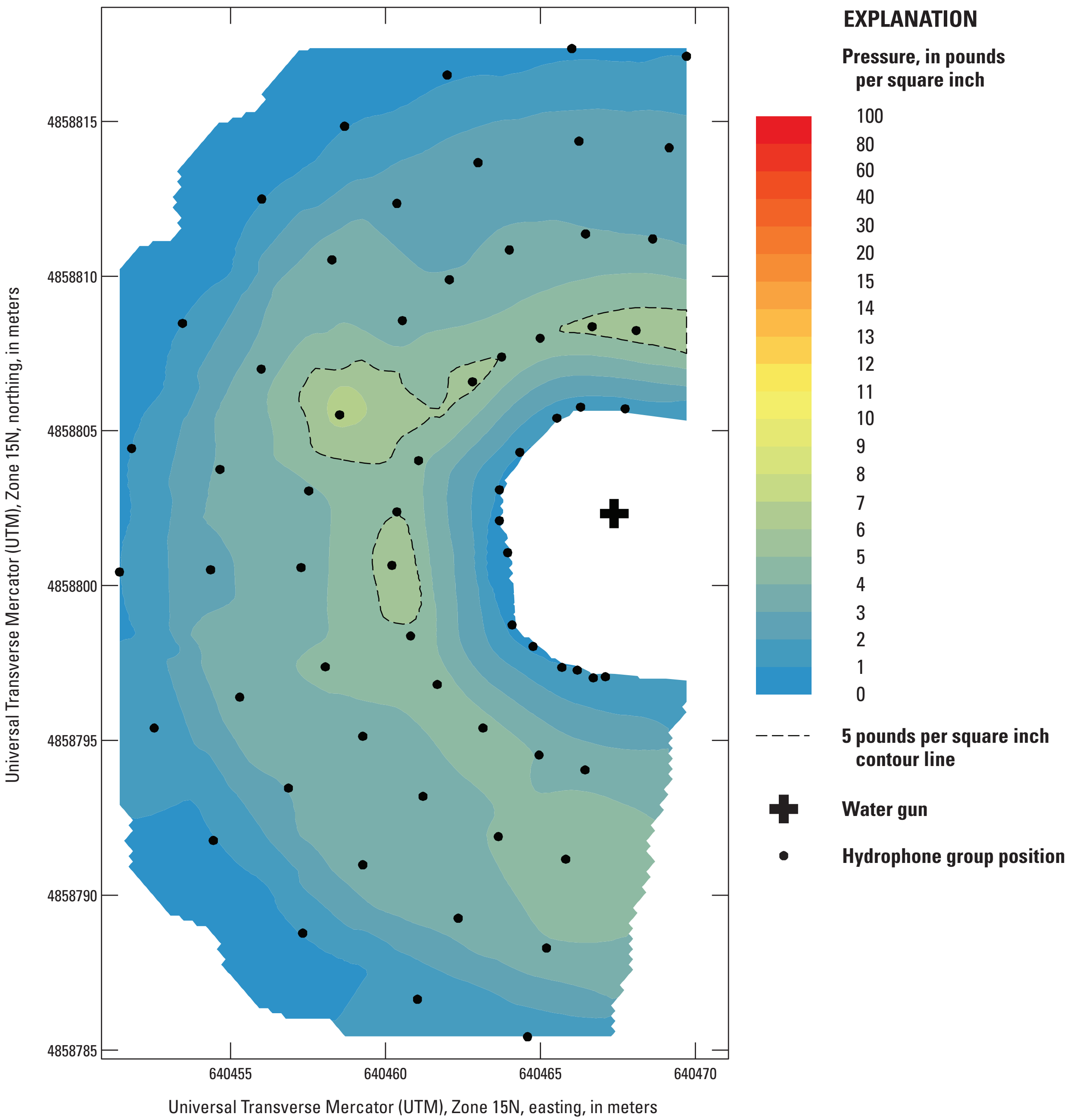

Figure 1–22. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 1 foot.

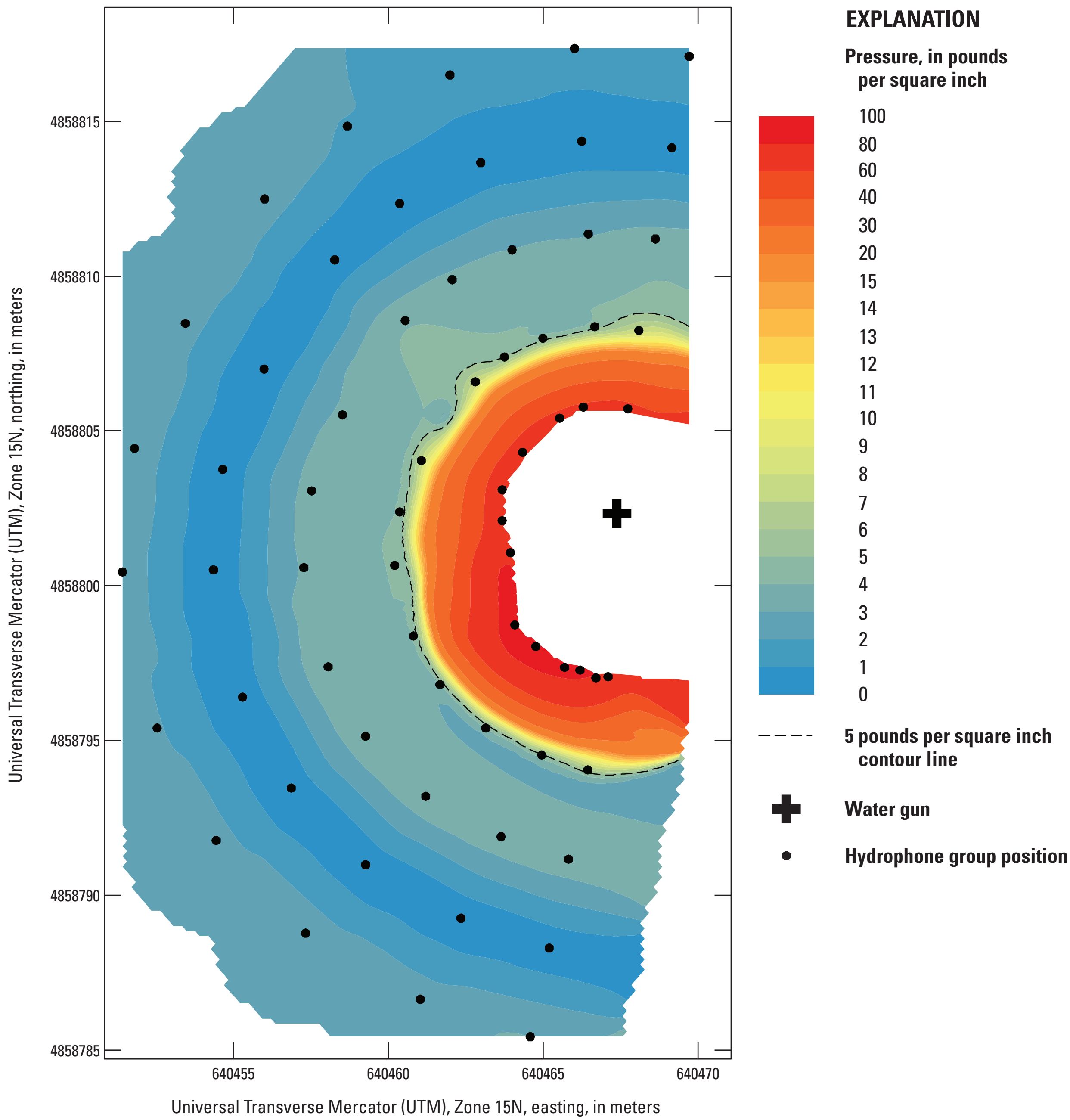

Figure 1–23. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 2 feet.

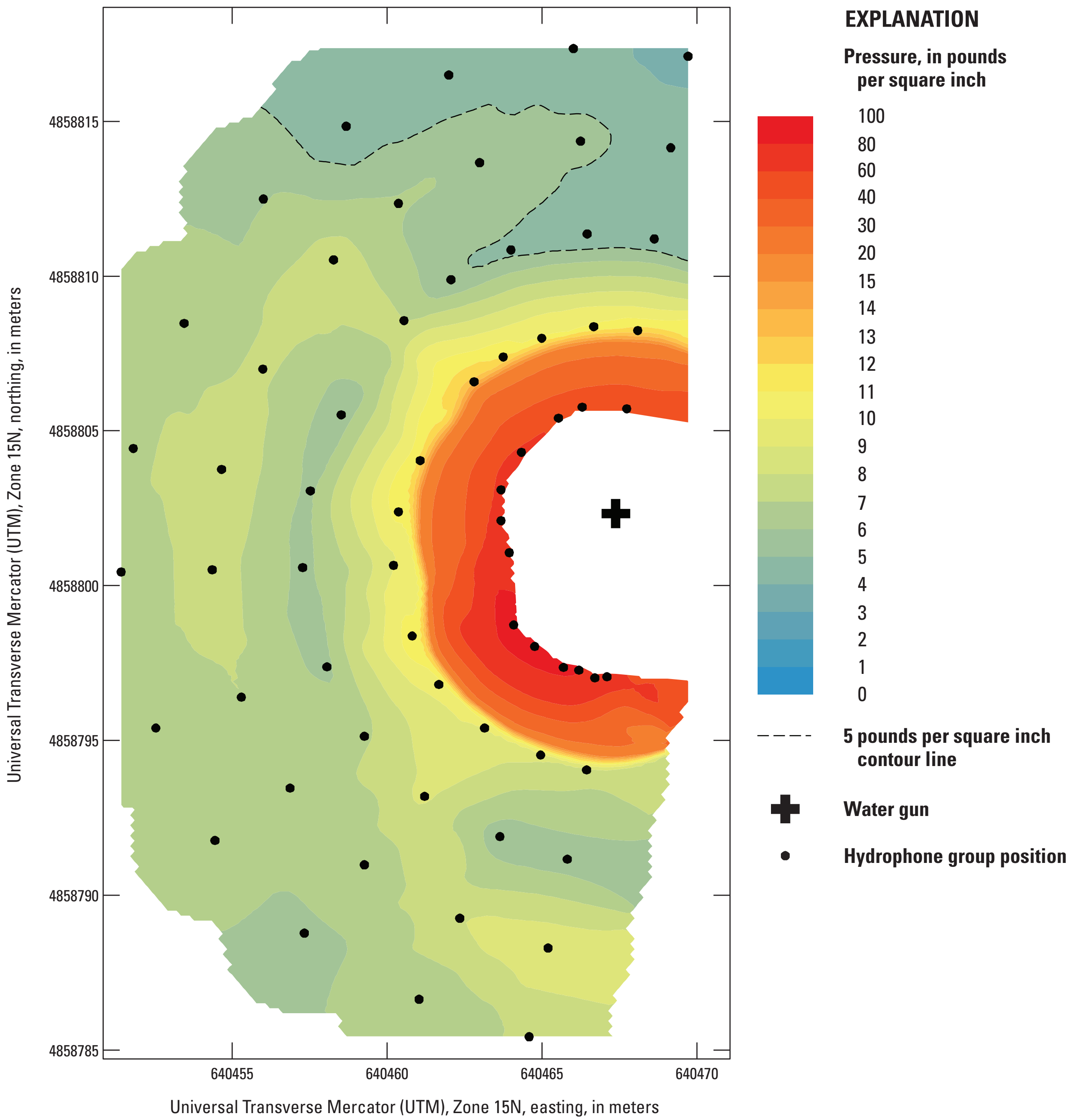

Figure 1–24. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 3 feet.

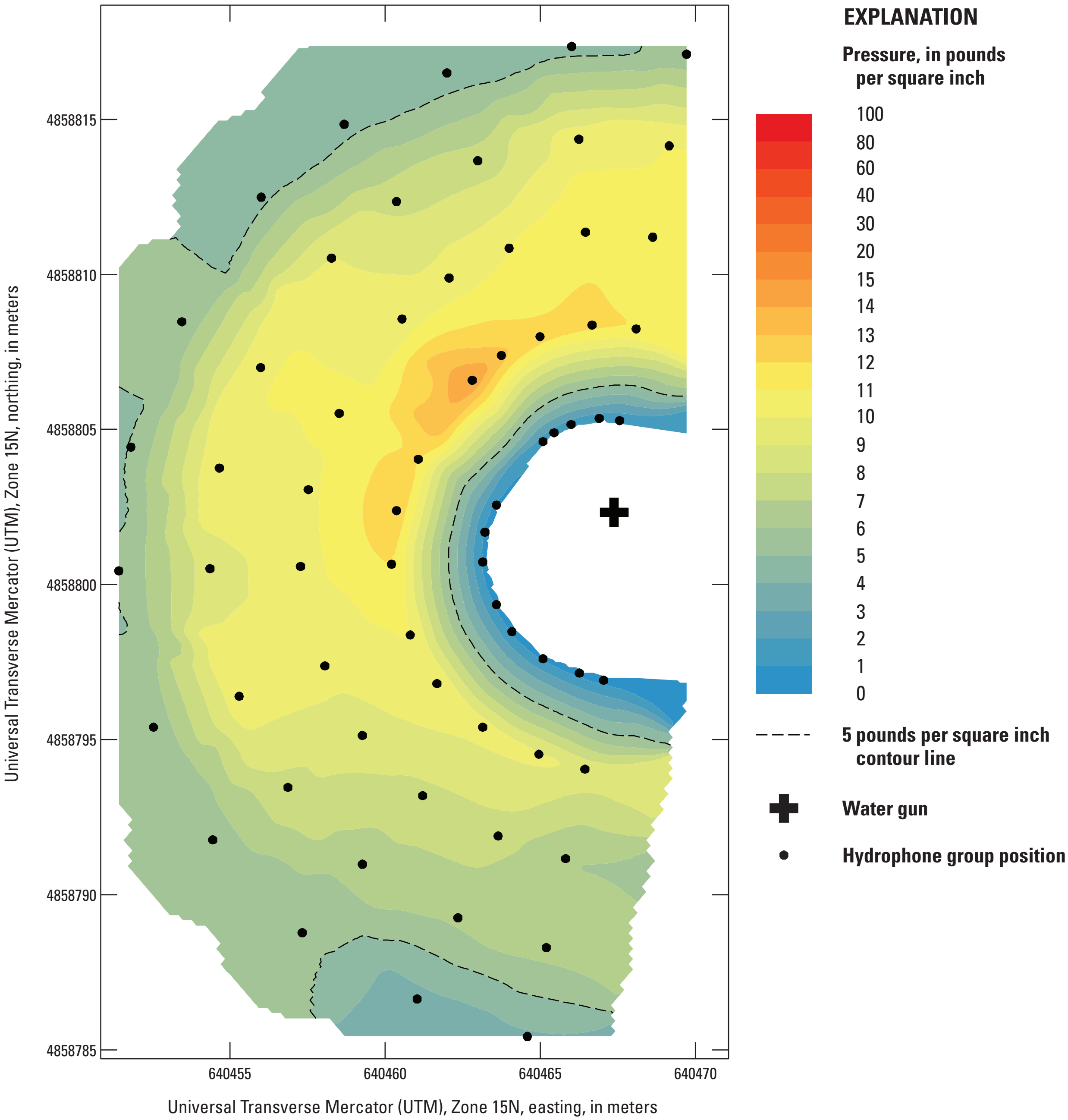

Figure 1–25. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 4 feet.

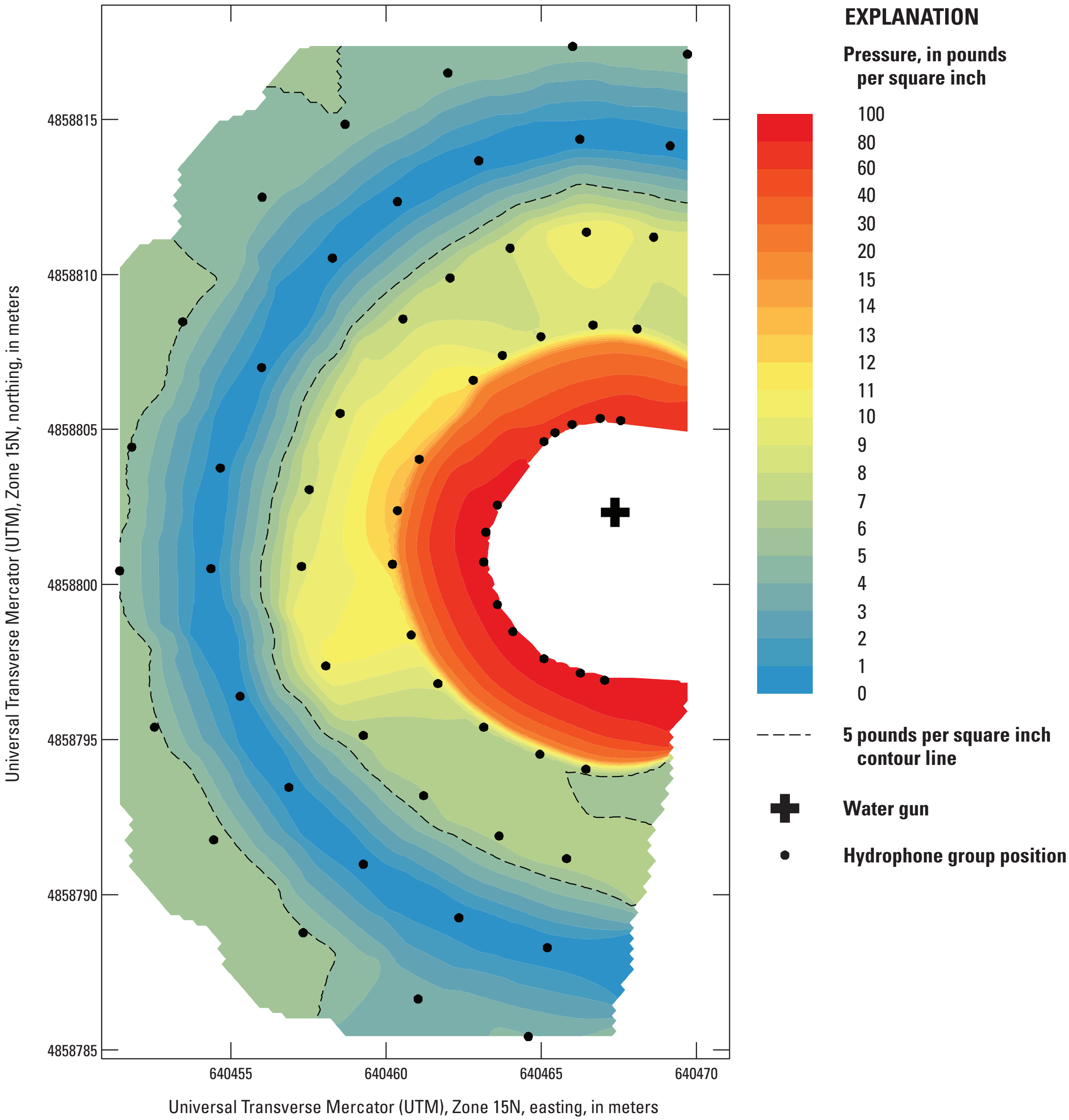

Figure 1–26. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 5 feet.

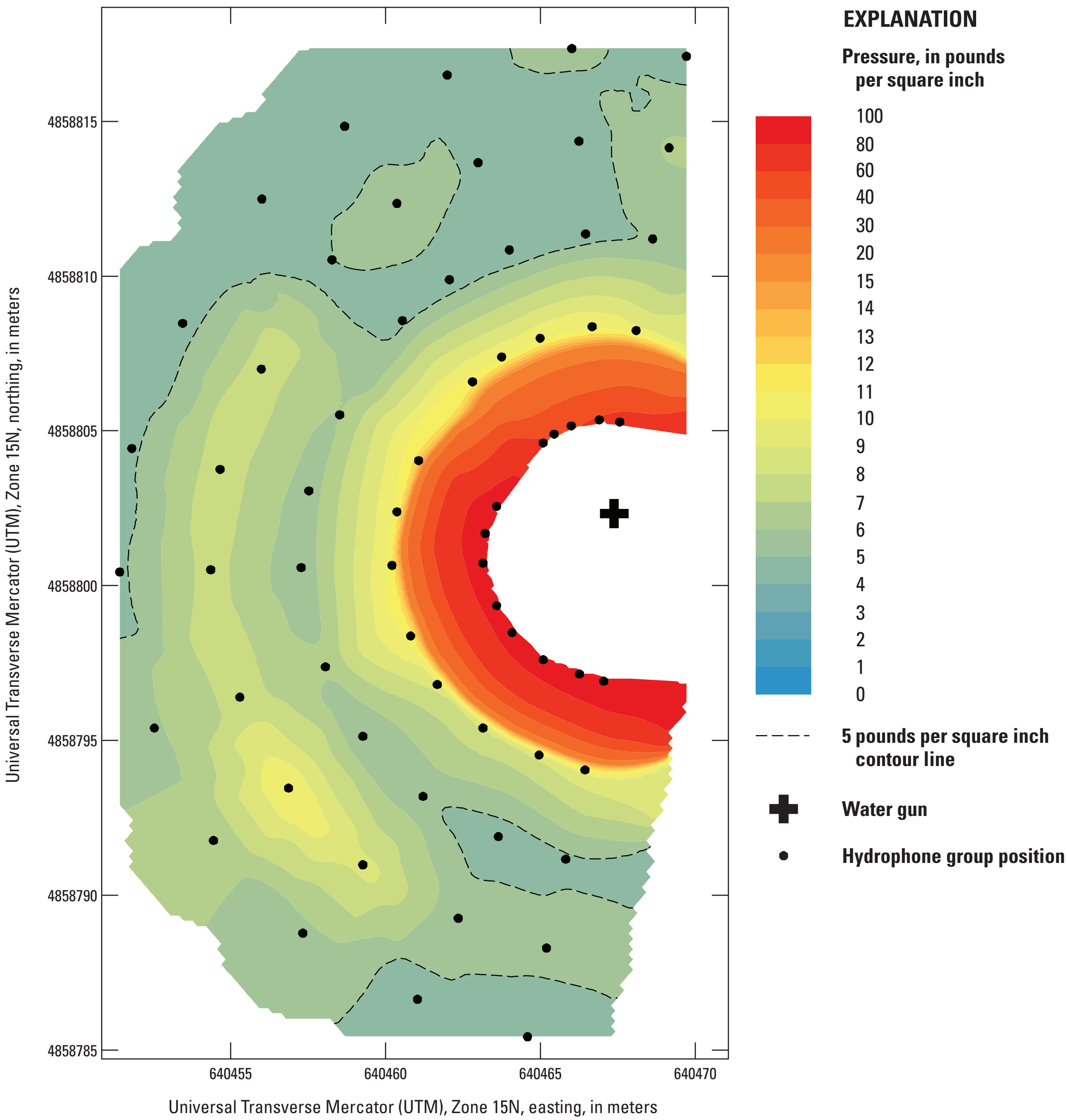

Figure 1–27. Pressure map from 80-cubic-inch water gun fired at 2,000 pounds per square inch, measurements at a depth of 6 feet.

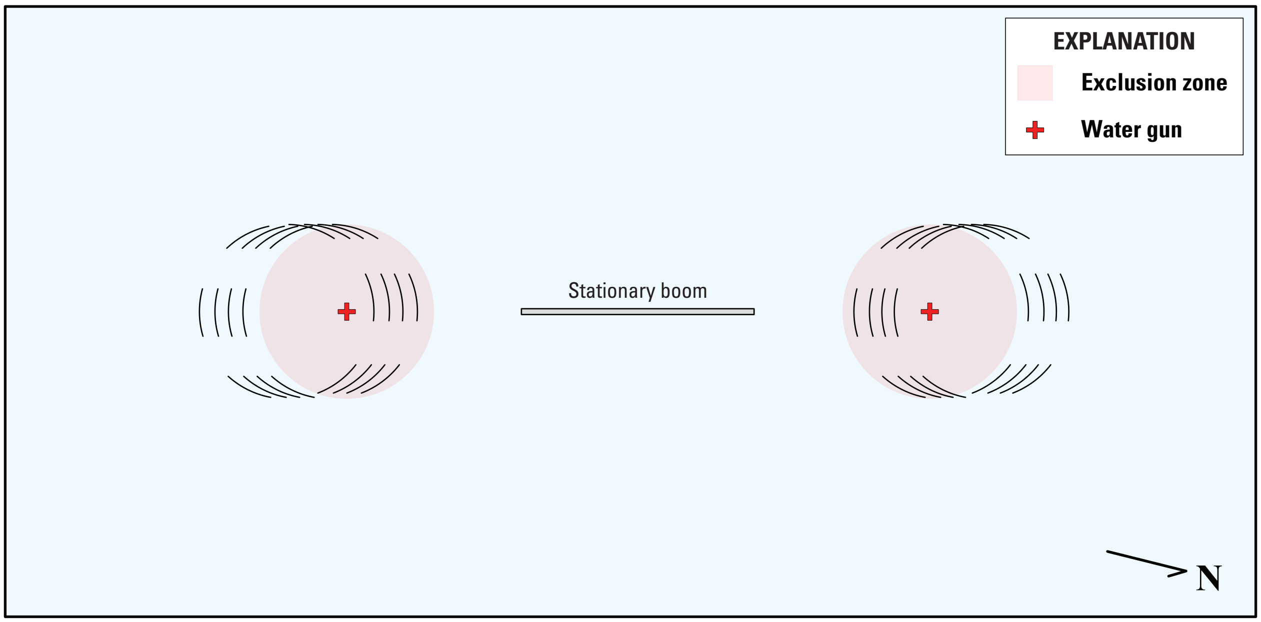

Figure 1–28. Equipment setup for the experimental barrier evaluation scenario.

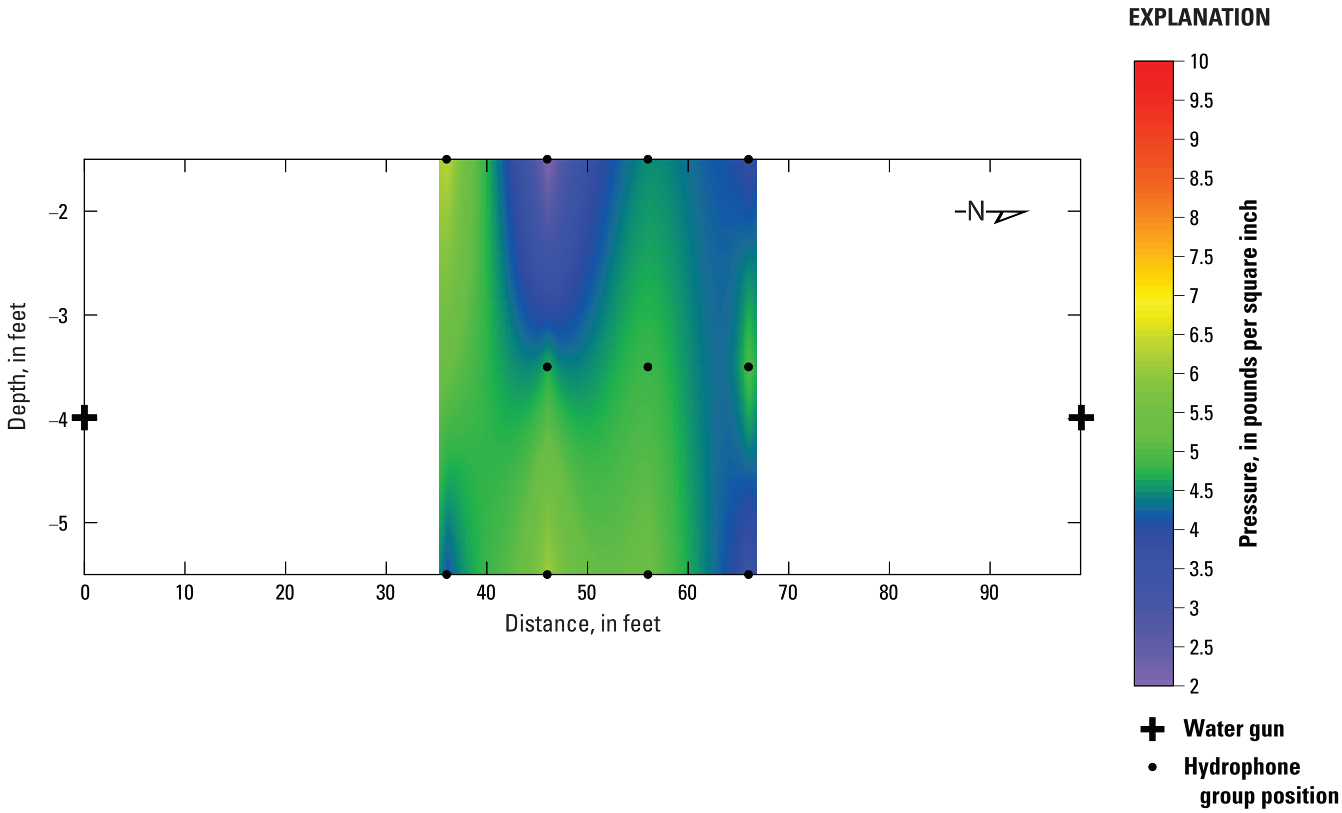

Figure 1–29. Pressure map from two 80-cubic-inch water guns both fired at 1,300 pounds per square inch, separated by 99 feet.

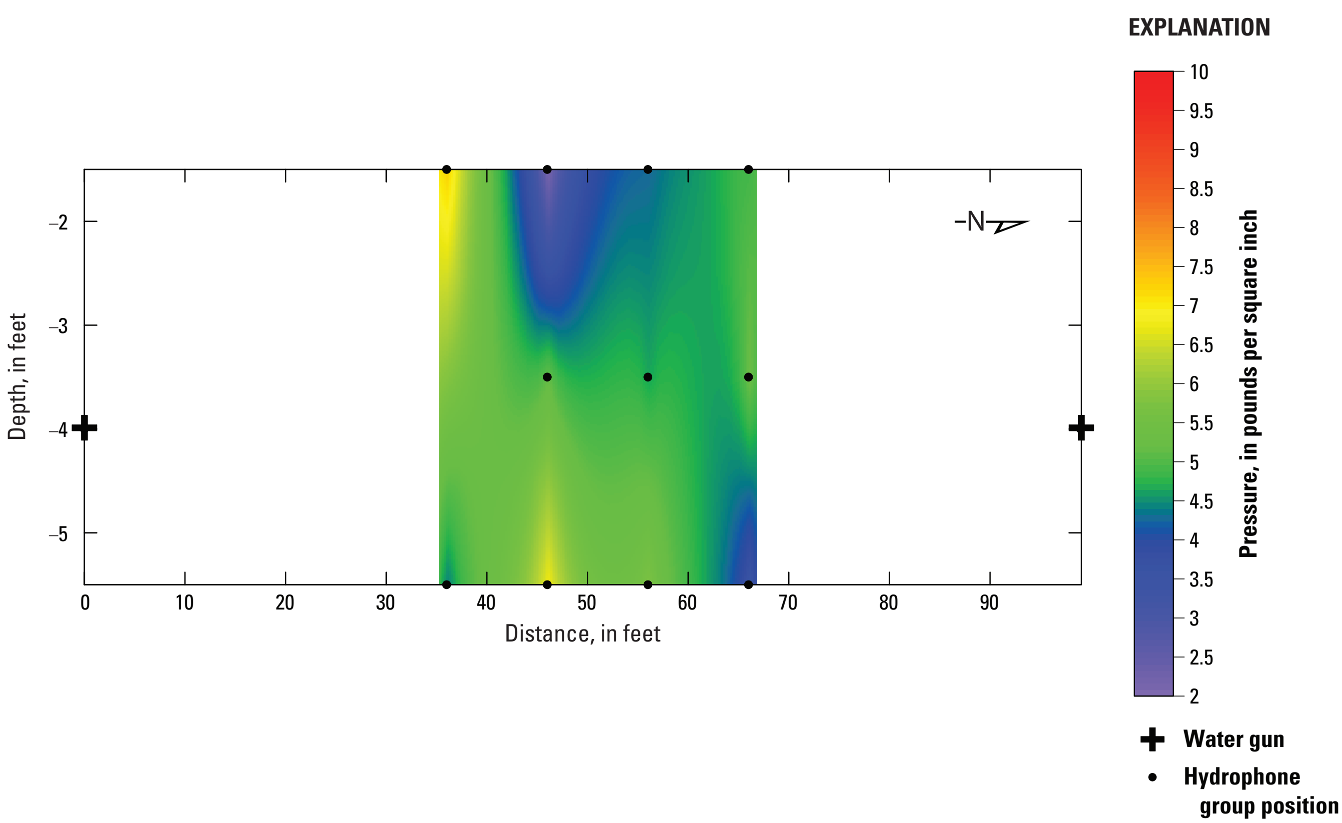

Figure 1–30. Pressure map from two 80-cubic-inch water guns fired at 1,500 pounds per square inch, separated by 99 feet.

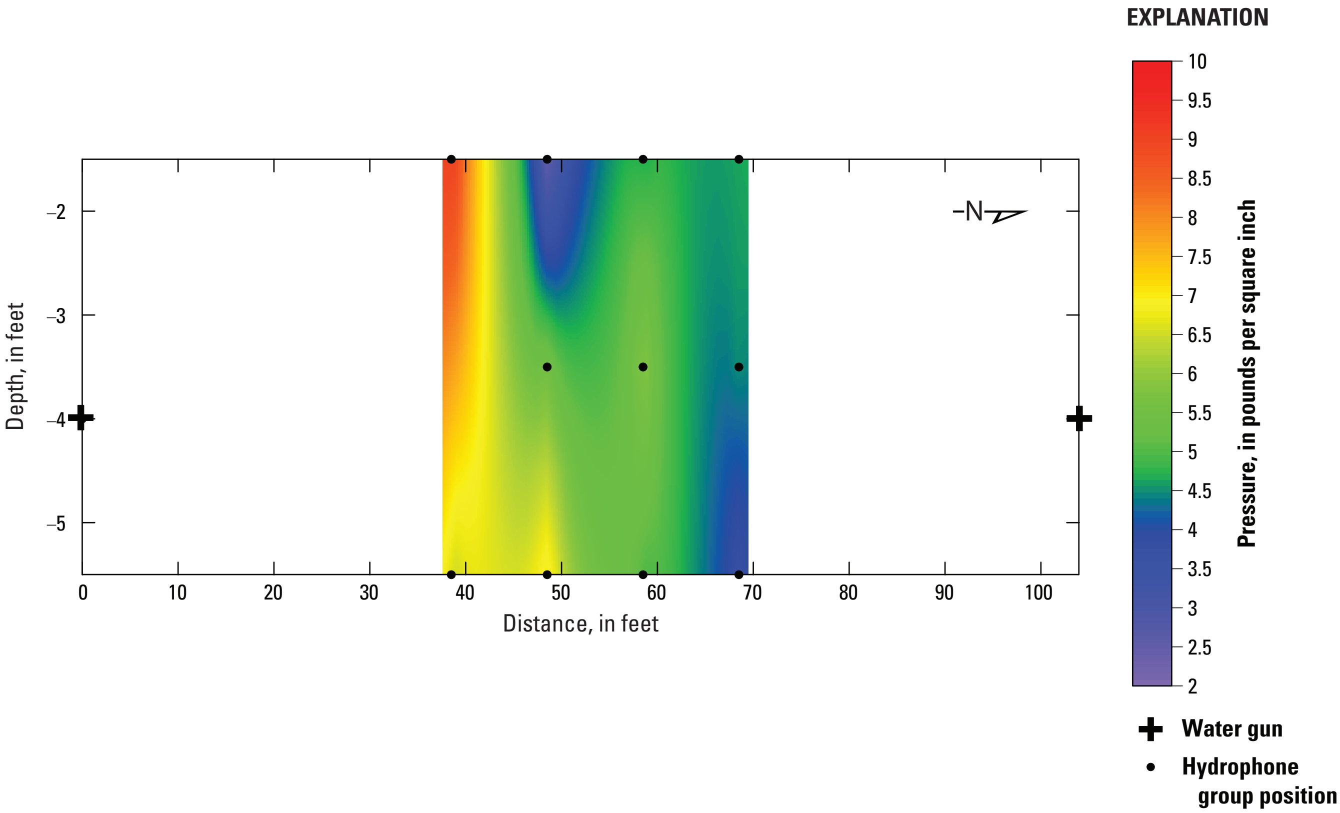

Figure 1–31. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 104 feet.

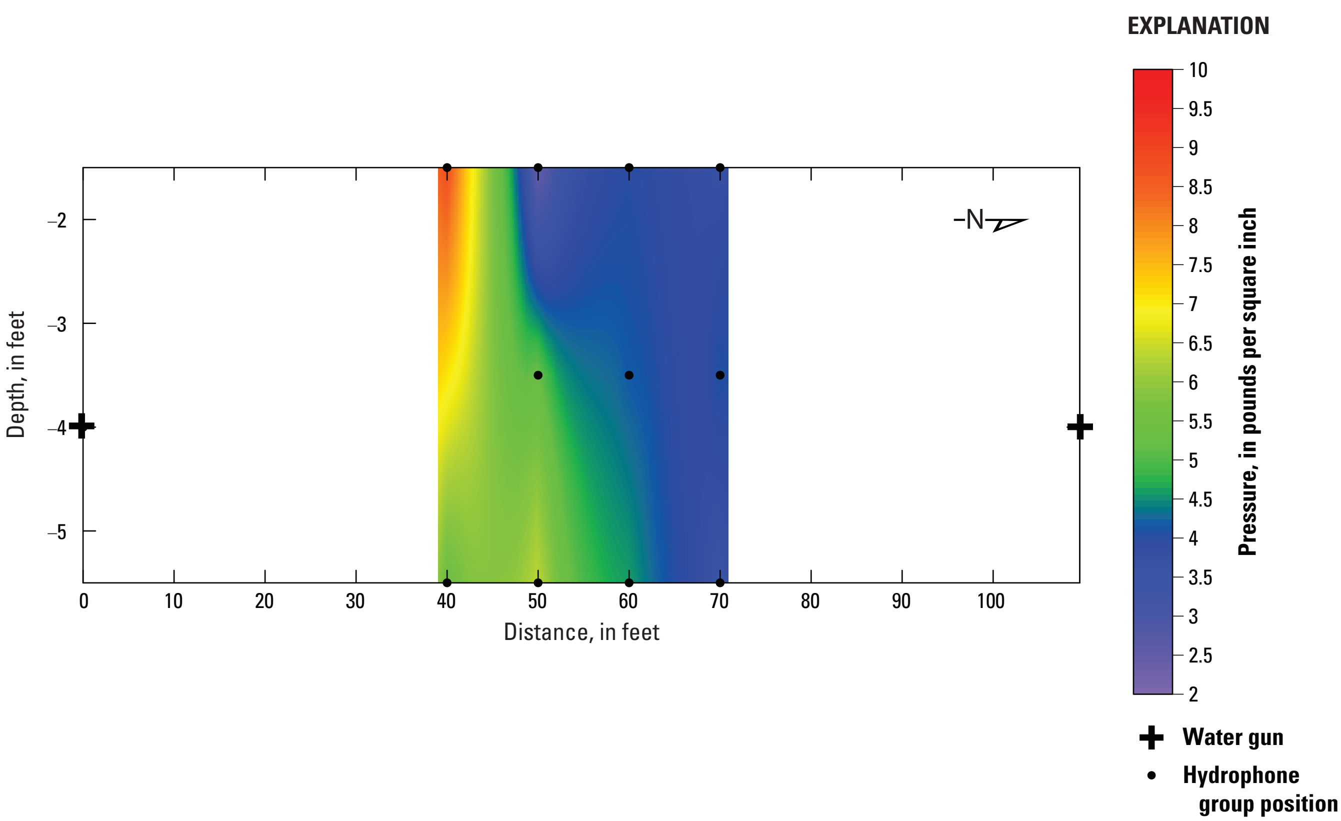

Figure 1–32. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 109.5 feet.

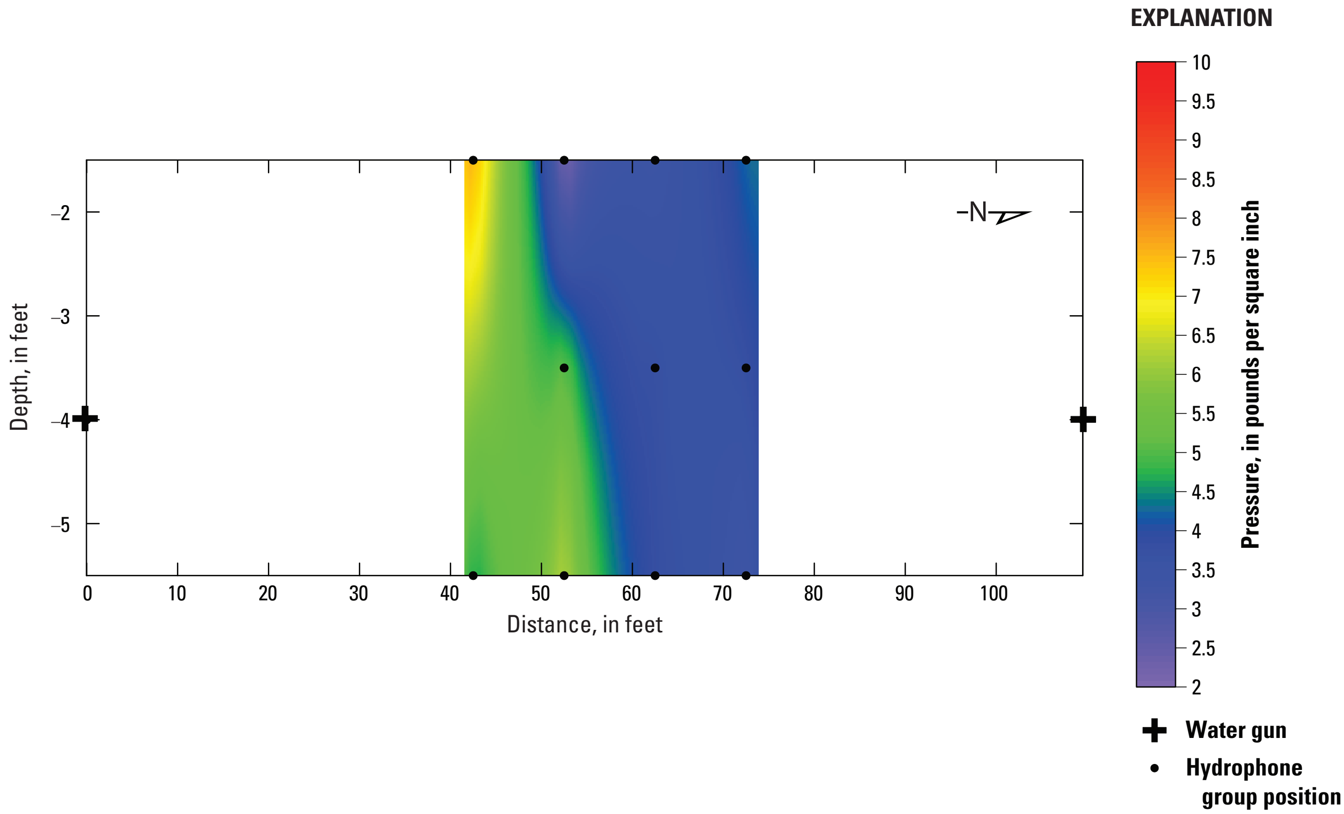

Figure 1–33. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 115 feet.

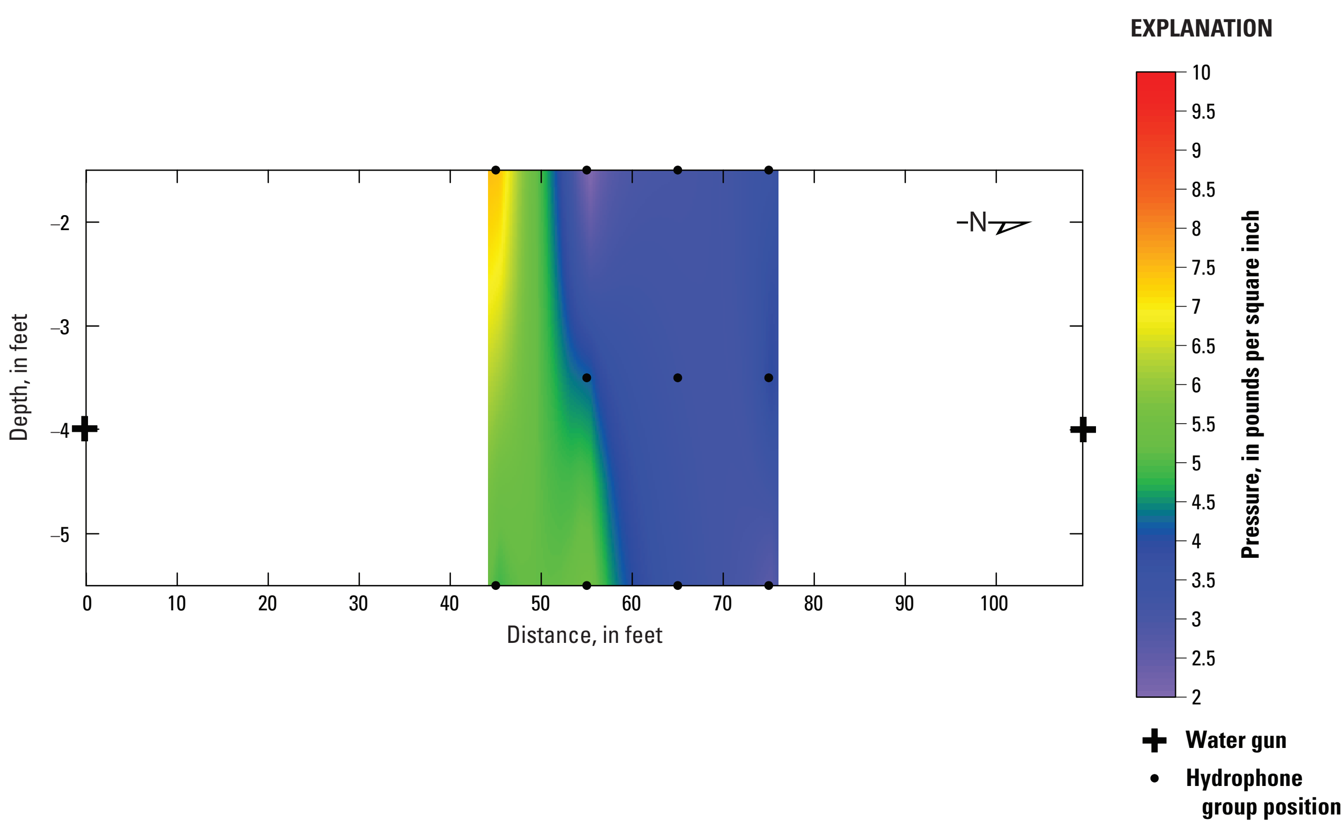

Figure 1–34. Pressure map from two 80-cubic-inch water guns both fired at 1,500 pounds per square inch, separated by 120 feet.

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