Flow Surveys in Steep Pennine Catchments

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INTRODUCTION

The standard approach to the planning of a short term flow survey generally starts with a desktop assessment. This study should identify all ancillaries, known hydraulic problem areas, the purpose of the study and the level of detail required for the flow survey.

Selection of flow monitor locations should depend on the purpose of the study, but generally will involve monitoring at key locations:-

1) Upstream and downstream of major ancillaries so that their performance can be confirmed.
2) At critical points in the network to enable verification of known hydraulic problem areas.
3) At critical points within the trunk sewers and/or major branches to allow assessment of any affects from major inflows.

The specific locations within the network should be chosen where the hydraulic conditions are most suitable. Particular locations are known to be unsuitable for flow monitoring and are best avoided. These include:-

1) Monitors located in the outgoing pipes to manholes where turbulence can lead to errors in readings.
2) Monitoring in locations where there is no dry weather flow, such as overflow pipes where it is unlikely that the calibration of the monitor will be possible.
3) Monitors located just upstream of CSO chambers with high weirs where backwater effects can lead to low velocities.
4) Monitors located downstream of throttle pipes and orifices where high velocities can occur.

The final selection of flow monitor locations and type should be determined by a pre-survey site inspection, carried out in the conjunction with the flow survey contractor, and should check the on site hydraulic conditions and location. Even with this rigorous planning and detailed site selection it has been found that many of the selected flow monitor sites in steep Pennine catchments were producing data that was at best poor and in many cases unusable.

DETERMINATION OF LIKELY POOR FLOW MONITORING SITES

Having identified that many sites can produce unreliable data an investigation was carried out to determine which sites these were likely to be. A different approach to the traditional flow survey could then be adopted which would prevent abortive survey work.

The reason for the poor quality data is usually that the actual conditions encountered are outside the performance range of the monitor or poor flow conditions mean that the measured values are not representative of the overall flow. The reasons for conditions being outside of the performance range are generally that either the depth of flow is too low or the velocity of flow is too high or a combination of the two.

Standard flow monitors require a minimum depth of flow of 100mm to operate satisfactorily, with an ADS monitor typically requiring approximately 50mm. In pipes of 225mm or less it is unlikely that the required depths will be observed for sufficient time to make monitoring accurate and equally weekly velocity calibrations can not be undertaken when the depth of flow is too low. It was, therefore, concluded that monitoring in small diameter pipes would generally lead to poor data return.

The second reason for flow monitoring conditions being outside the performance polygon is the velocity of flow being too high. A study was, therefore, carried out to determine critical sewer gradients for flow monitoring.

STEEP PIPE ANALYSIS

Three catchments from the Calder Drainage Management Zone were selected as being typical of steep Pennine catchments, these being Moldgreen, Meltham and Sowerby Bridge. Meltham and Moldgreen had already undergone a short-term flow survey study, which had proved difficult and costly for the latter, due to the problem of finding suitable survey locations and the lack of flow response during typical rainfall events.

Each model was run in HydroWorks with simulated rainfall events. Two storms and a dry day were selected to give the variation of flows required and thus show a variation of flow conditions within each pipe.

The two rainfall events used within the study were taken from the South West Time Series Rainfall (SW TSR). These were selected because the SW TSR closely matched the conditions experienced in these Pennine Regions, namely a similar Standard Annual Average Rainfall (SAAR) of approximately 900mm and Urban Catchment Wetness Index (UCWI) parameters for Winter and Summer and matching M5-60 values, as indicated in the Table 1 below:

Table 1:Comparison of Rainfall Characteristics

	Sowerby Bridge	Moldgreen	Meltham	South West Time Series
SAAR mm	1050	900	1200	930
UCWI (Winter)	144	140	150	140
UCWI (Summer)	110	98	120	98
M5-60 series	19	19	19	19

Storm Events 22 and 31 were selected. Both meet all the flow survey event criteria as specified by the WaPUG Code of Practice for the Hydraulic Modelling of Sewer Systems (Version 2), namely over 5 mm total rainfall depth and a rainfall intensity greater than 6 mm/hour for over 4 minutes. Experience with flow survey work in the Pennine region has shown that storms that only just meet the WaPUG Criteria are unlikely to generate sufficient response in the pipes for accurate flow measurement. Event 31 was chosen as it most closely replicated the typical conditions needed for adequate flow monitor response. Event 22 was chosen as more representative of conditions likely to be encountered during survey work that may create velocities beyond the working range of the monitoring equipment.

Both events, and a typical dry day, were run using the relevant files in HydroWorks v5.0 and the results were then exported into Excel for analysis. All pipes of 300mm diameter and above were considered as possible monitor locations. Depth and velocity criteria are normally specified as values occurring for 75% of the storm. It quickly became apparent that to extract these values for all locations and storms would require a high amount of data analysis. To avoid this a sample set of depth and velocity hydrographs was selected at random and the depths and velocities calculated for 75% of the storm. These values were then compared with the maximum depths and velocities respectively, to produce scaling factors.

Maximum depths and velocities for each location and for each storm were then extracted from the HydroWorks prn files and re-scaled to the equivalent 75% duration values. This approach was considered to be sufficiently accurate for the purposes of the study. The re-scaled values were then compared with the range of accuracy of both standard and ADS flow monitoring equipment (fig. 1).

RESULTS FROM STEEP PIPE ANALYSIS

The results have been plotted on the Performance Polygons shown in Figure 1. These polygons show the boundary of accurate recording of the two main types of flow monitor. It is clear that the response in these catchments generally demonstrates that the pipe flow conditions are of low depth and high velocity. This is indicative of steep gradient pipes within these catchments. The polygons also show that the majority of the points plotted lie outside the range of the performance of flow monitors. A summary of the plotted results can be seen in Table 2 and shows the numbers of pipes that have been tested and those that might be suitable for monitoring as part of a study.

Table 2:Summary of Results

Criteria	Number
Pipes tested	867
Pipes included in methodology (all above 300mm)	537
DWF – Pipes failed performance polygon criteria	468
DWF – Pipes monitored by Standard (ADS)	65 (4)
Event 22 – Pipes failed performance polygon criteria	319
Event 22 – Pipes monitored by Standard (ADS)	150 (68)
Event 31 – Pipes failed performance polygon criteria	326
Event 31 – Pipes monitored by Standard (ADS)	146 (65)

In order to identify conditions that limit the application of flow monitoring, the gradient of each pipe was calculated and then plotted against pipe size. The results are shown in figures 2 to 4 for each of the events tested. The points marked with squares indicate results beyond the range of either type of monitor, those with triangles are within the range of ADS monitors but beyond the range of standard monitors, and the remainder marked with circles are within the range of both types of monitor.

The results show the following:-

1. Dry weather flow monitoring in pipes smaller than 450 mm or with gradients steeper than 0.033 (1 in 33) is unlikely to be successful.
2. There is minimal advantage in using ADS monitors in pipes bigger than 900 mm diameter.
3. Monitoring in pipes larger than 900mm diameter and steeper than 0.023 (1 in 43) is unlikely to be successful.

For pipes between 300 mm and 900-mm diameter, the black and grey lines respectively in Figures 2 to 4 give the limiting gradients for ADS and Standard monitors. The values summarised in Table 3 refer to the maximum recommended gradient for each pipe size above which monitoring should not be attempted.

Table 3:Summary of maximum permissible gradients for each monitor type

Pipe Size (mm)	**Limiting Gradients**			
	ADS		**STD**	
300	0.067	1 in 15	0.012	1 in 80
375	0.071	1 in 14	0.019	1 in 53
450	0.071	1 in 14	0.022	1 in 46
525	0.067	1 in 15	0.024	1 in 42
600	0.062	1 in 16	0.022	1 in 46
675	0.055	1 in 18	0.021	1 in 48
750	0.050	1 in 20	0.017	1 in 60
825	0.045	1 in 22	0.014	1 in 69
> 900	0.042	1 in 24	0.013	1 in 74

It should be noted that there is a considerable scatter of results. In part this is due to simplifications made in the analysis and in part due to the inherent variability in the sewer networks. The limiting gradients in table 3 should be seen, therefore, as a general guide for the purposes of planning flow surveys only.

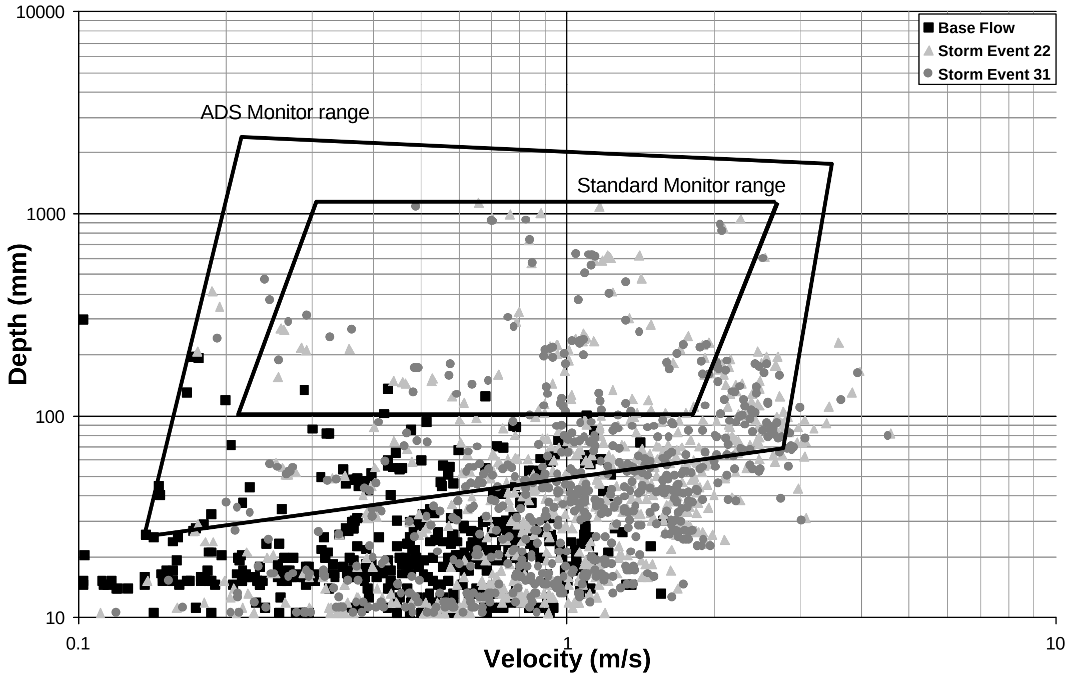

Fig. 1: Polygon comparing 75 % depth and velocity for each pipe, with the range of accuracy of flow monitors.

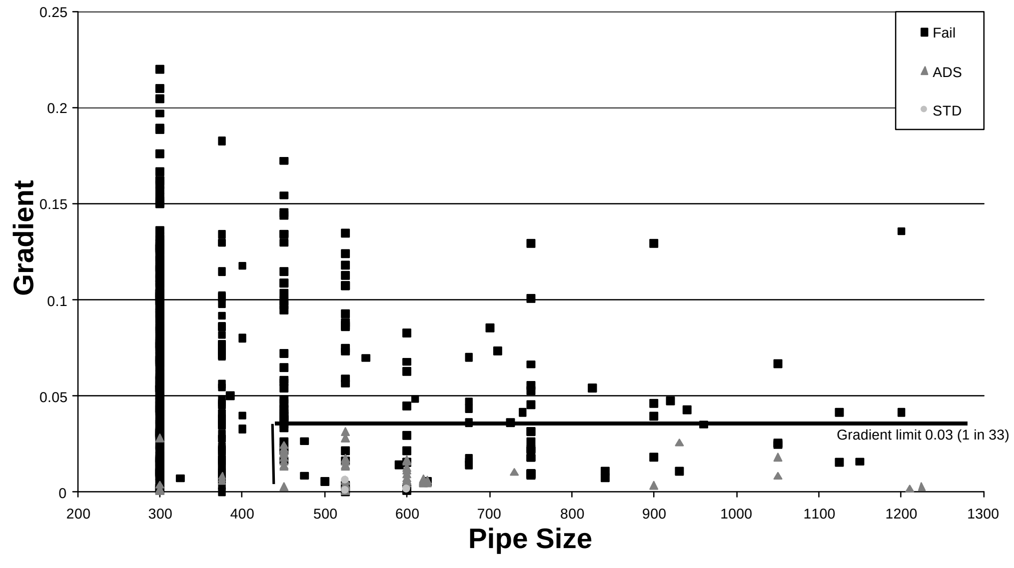

Fig.2: Graph showing the influence of gradient and pipe size on flow monitoring performance and recommended maximum gradients for monitoring in Dry Weather Flow Conditions

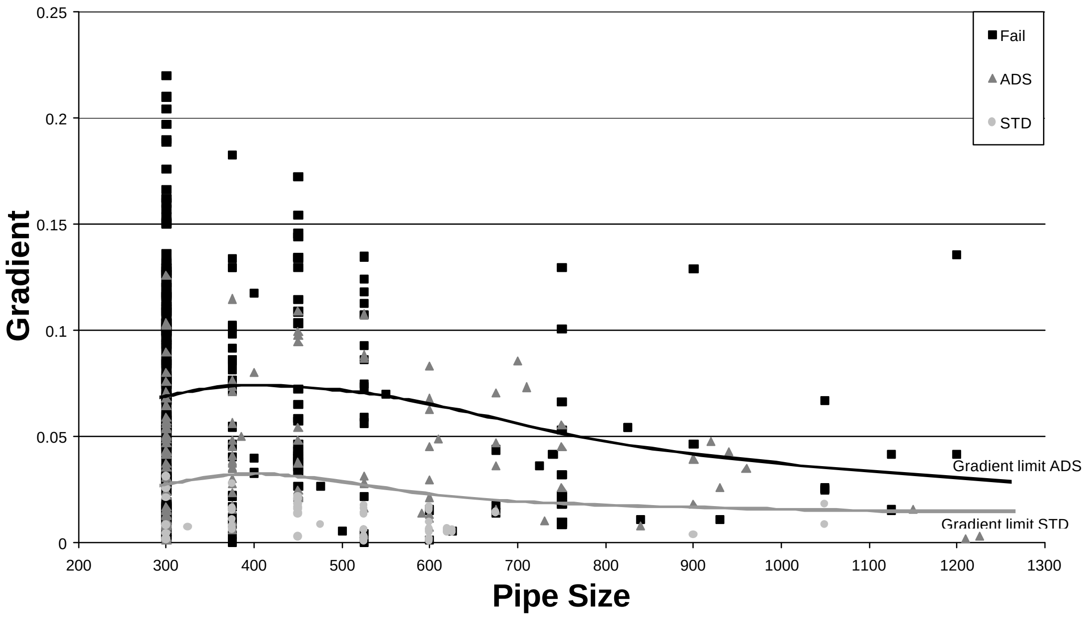

Fig. 3: Graph showing influence of gradient and pipe size on flow monitoring performance and recommended maximum gradients for flow monitoring, based on Event 22.

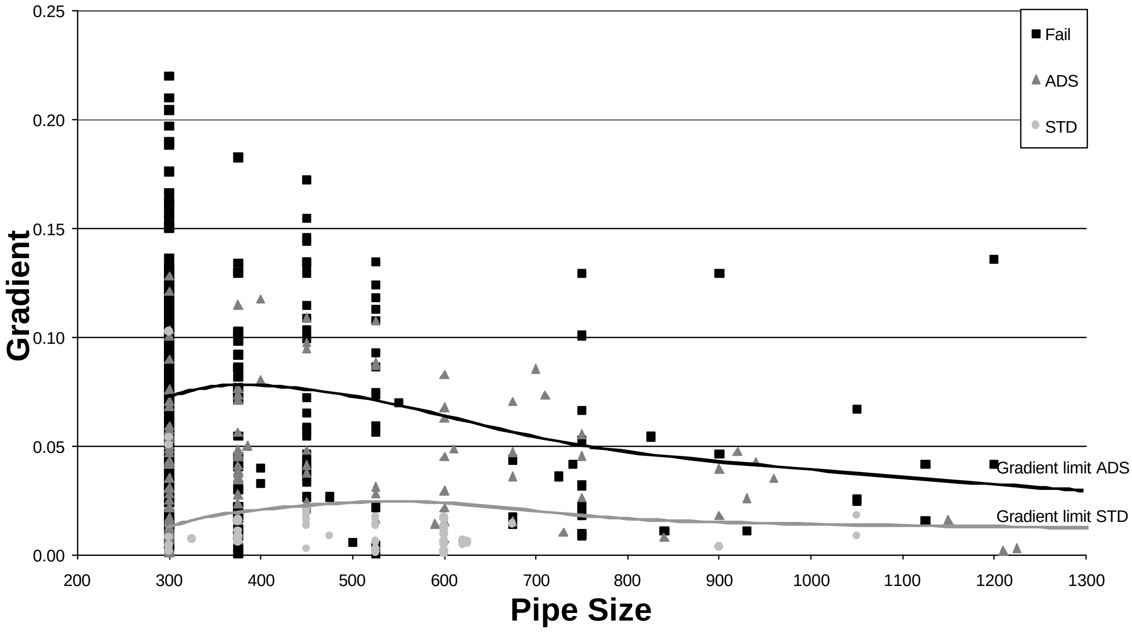

Fig. 4: Graph showing influence of gradient and pipe size on flow monitoring performance and recommended maximum gradients for flow monitoring, based on Event 31.

CONCLUSION ON EFFECTS OF PIPE SIZE AND GRADIENT

The study has demonstrated that, without some rules to restrict the application of flow monitoring in steep catchments, there is the potential for significant expenditure on flow survey work with little useful output being produced.

On the basis of the study it appears that rules can be set out to significantly reduce the risk of unproductive flow survey work. These rules are set out above. Subsequent use of the rules on real studies has shown that unproductive survey work is substantially reduced but can not be eliminated entirely. It has also shown that some catchments have pipe sizes and gradients such that verification by flow survey is almost impossible. In such cases an alternative method of gaining confidence in a model is required. The following sections describe a sensitivity analysis used for that purpose.

SENSITIVITY ANALSIS

This sensitivity analysis describes a method of gaining confidence in a hydraulic model where verification by flow survey is impractical. The sensitivity analysis is based upon identifying particular points in the network where performance assessment is important (the strategic performance points) and then checking the values of data items that most influence system performance at these points (the key data items).

STEP 1: COLLECT INITIAL INFORMATION/IDENTIFY KEY DATA ITEMS

The first task is to bring together all relevant information that is readily available. The documentation should include a specific and clear statement of the purpose for which the hydraulic model is to be used.

Using information from the model build report, a list of key data items should be drawn up which will be dependent upon the purpose of the model. An example list is included in Table 4.2.

STEP 2: STRATEGIC PERFORMANCE POINTS/SENSITIVITY ANALYSIS

The purpose of this step is to determine the key data parameters that most influence the performance of the hydraulic model. Although these will vary from model to model, they will, in general, group into three categories. In order of importance these categories will normally be:-

(i) Contributing areas, impermeability factors, pipe sizes.

(ii) Ancillary data especially throttle sizes, weir levels and pumping rates, bifurcation data and soil type.

(iii) Pipe roughness, silt and treatment works data.

The procedure for undertaking a sensitivity analysis is as follows:-

(i) Run the model with a 2 year return period design storm of the critical duration.

(ii) Identify strategic performance points in the system and tabulate the results from the design storm for peak flow rate, maximum water level and, where appropriate, flooded volume.

Table 4.1:Example Strategic Performance Points

	Purpose of Model		
	DG5 & Area Flooding	**Aesthetic Performance of CSOs**	**Water Quality Performance of CSOs**
Example Strategic Performance Points	Pipe immediately upstream of flooding location. Pipe immediately downstream of flooding location. Main outfall pipe from drainage area.	Pipe immediately upstream of CSO. Pipe immediately downstream of CSO. Main outfall pipe from drainage area.	Pipe immediately upstream of CSO. Pipe immediately downstream of CSO. CSO outfall pipe. Main outfall pipe from drainage area.

(iii) For each key data item, vary the data value in turn. Re-run the model and record the revised values at the strategic performance points. The recommended change for each data item is given in Table 4.2 below. The run reference for each run should also be recorded in the table. Properly recording the output from each run in this way will assist in checking and auditing.

Table 4.2:Recommended Change in Key Data Items for Testing

Key Data Item	**Recommended Variation**
Contributing Area	± 10%
Impermeability	± 10%
Pipe diameter/upstream of CSOs	± one size
Pipe diameter/downstream of CSOs	± one size
CSO outfall pipe diameter	± one size
CSO throttle dimension	± 10%
CSO weir level	± 50 mm
Bifurcation outlet pipe diameter (minor branch)	± one size
Bifurcation outlet pipe level (minor branch)	± 50 mm
Pumping rate	± 10%
Default pipe roughness	± one roughness increment
Identified silt levels	± 20% of pipe diameter
Soil factor	± one factor
Population	± 10%

Having completed the necessary runs, the effect on flow levels and flooding volumes at the key data points may be reviewed.

STEP 3: CATEGORISE KEY DATA ITEMS

Key data items may now be categorised according to their importance in influencing the model output at key data points. Table 5.1 gives the variation in peak flow, maximum water level and flooded volume that sets each data point into one of the categories A, B or C.

Table 5.1:Variation in Performance for Categorising Key Data Items

Category	Variation		
	Peak Flow	Depth	Flooded Volume
A	≥ ± 10%	≥ ± 20%	≥ ± 10%
B	≥ ± 5%	≥ ± 10%	≥ ± 5%
C	< ± 5%	< ± 10%	< ± 5%

All key data items will now have been categorised A, B or C, according to their influence overall on model performance at strategic data points.

STEP 4: CHECK AND REVIEW KEY DATA ITEMS

All key data items categorised A must be checked for accuracy and any assumptions that have been made should be reviewed. A similar check and review of a random 10% selection of all Category B data should be undertaken. Where appropriate, there should be further checks and reviews of Category B data. There should be no need to check or review any Category C data unless an obvious error has been made.

The model should be updated with revised key data as a result of the above check and review process. The review and any changes made must be fully documented.

STEP 5: IDENTIFY NEED/COLLECT FURTHER INFORMATION

The check and review process in Step 4 will identify whether further evidence is needed to confirm or improve the accuracy of any Category A or B key data items. In reaching this decision the time and cost estimated to obtain further information should be balanced against the perceived benefit. Should further work be considered inappropriate the model is updated and finalised and the model build report completed (Step 8).

Further information may be available in the form of record plans and drawings, survey data, pumping station records and wastewater treatment works records. Of particular interest will be historic information concerned with system performance. This may include information on flooding (DG5 and Area Flooding Registers), CSO spills (FR0466 and Macro-invertebrate surveys), press reports and public complaints.

STEP 6: TEST MODEL AGAINST HISTORIC PERFORMANCE DATA

This will not be a precise test in the sense of formal verification using short term flow survey data. The model should be run for the critical duration events for the 1 year, 5 year, 10 year and 30 year return periods. A plan should be marked up showing:-

(i) The location, frequency and associated volume of flooding.

(ii) The setting and maximum continuation flows from CSOs (expressed in multiples of dry weather flow).

(iii) The one year return period spill volumes from each CSO.

(iv) The five year peak spill discharge from each CSO

The plan should then be annotated to show historic information and a judgement made of its fitness for purpose.

The decision as to whether or not the model sufficiently reproduces known historical performance will then be made.

STEP 7: NEED FOR/PLAN/UNDERTAKE ADDITIONAL SURVEY WORK

The decision to undertake further survey work will be based on the estimated cost-benefit of that work.

Additional survey work may take the form of:-

(i) Further surveys of key contributing areas. This may be used to confirm the type of drainage area, resolve uncertainties over network connectivity, identify boundaries or determine impermeability.

(ii) Additional survey of ancillaries. This may include additional geometric and level measurement of chambers, pump tests, and block-off tests to determine CSO throttle characteristics. During these surveys all pipe diameters should be checked and information on silt depths and scum marks recorded.

(iii) Flow and level surveys. This will usually be limited to flow survey logging of the main outfall and level recording of important ancillaries.

After the survey work is agreed and undertaken, the model is updated and then compared again with the historic data (Step 6). It is unlikely that a second additional survey would be beneficial on cost grounds under this procedure.

STEP 8: DOCUMENT ALL CHANGES, COMPLETE MODEL BUILD REPORT

The final step is to update and run the model and complete the Model Build Report. The model should be carefully checked for instabilities and any obvious anomalies. Careful documentation is of paramount importance at each stage of the proceedings and in the final Model Build Report.

CONCLUSIONS ON SENSITIVITY ANALYSIS

The methodology described above is intended to provide a robust procedure for gaining confidence in hydraulic models where flow surveys are impractical because of the characteristics of the drainage area and/or are inappropriate on cost-benefit grounds.

When used correctly, the procedure should not lead to a full scale flow survey being undertaken, nor unduly lengthen the model build process.

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